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SMALL TURBINE TECHNOLOGY REVIEW

I. C. Oelrich
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July 1985

Prepared for

Office of the Under Secretary of Defense for Research and Engineering

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This study, for OUSDRE (Research and Advanced Technology, Military Systems Technology), examines the nature of the small gas turbine development process for military applications, attempts to identify gaps between current programs and probable future needs, and makes program recommendations for acquiring desirable new turbine technology.

Small turbines are found to fall into one of four categories: man-rated, expendable, auxiliary power, and ground vehicle engines. The technical requirements of each category are reviewed and possible R&D opportunities identified.

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General Electric Company
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United Technologies, Pratt and Whitney
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CONTENTS

GLOSSARY

AIPS	Advanced Integrated Propulsion System
ALCM	Air-Launched Cruise Missile
APU	Auxiliary Power Unit
FSED	Full-Scale Engineering Development
IR&D	Independent Research and Development
LCV	Light Combat Vehicle
LHX	Light Helicopter Experimental
MBT	Main Battle Tank
PR	Pressure Ratio
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
SLCM	Sea-Launched Cruise Missile
TIT	Turbine Inlet Temperature
TOGW	Takeoff Gross Weight
TSFC	Thrust Specific Fuel Consumption

SUMMARY

A. INTRODUCTION

This paper reports the results of a study conducted for the Office of the Deputy Under Secretary of Defense (Research and Advanced Technology, Military Systems Technology). The study examines the nature of the development process for small gas turbine engines for military applications, attempts to identify gaps between current programs and probable future needs, and makes program recommendations for acquiring desirable new turbine engine technology.

Small engines are considered in this study to have power levels up to the range of approximately 2000 hp or pounds thrust.

Small gas turbines are important to the military, being used in a wide variety of applications such as cruise missiles, battle tanks, helicopters, jet trainers, mobile electric power units, and auxiliary power units. The diversity of these applications, involving many agencies, complicates the coordination of technology programs and essentially precludes single agency responsibility for small engines. The resulting fragmentation of effort and the special problems of small turbines due to their smallness have not allowed their technology to advance to the level of large turbine engines.

B. OBJECTIVE

It is of interest to determine whether technology programs for turbine engine components or demonstrator engine programs can be devised which offer major technology gains and which can be directly applicable to the broad range of military application.

It is this problem which is addressed in this report; in particular, the question was whether a single demonstration engine, or at least very few, could serve all small engine needs.

C. APPROACH

Information for the analyses of this report was gathered by visiting all government agencies involved in the research and development of small turbine engines, and by visiting all U.S. industries active in small turbine engine development and production.

Discussion with these engine groups brought out their views of where the needs and opportunities in future small engines lie and what they saw as appropriate R&D programs. More importantly, during these discussions with the engine groups the general approach to engine development became clear as well as some of the problems with that approach.

The need for advanced small engine technology depends on future missions. The likelihood of particular future missions is estimated by extrapolating from current missions and analysis of what missions may become feasible and have high payoff if engine technology is improved.

Payoffs of technology improvements are calculated for some missions to compare the savings resulting from using new technology to the cost of the technology program.

From all of the above program recommendations are made.

D. CHARACTERIZATION OF THE SMALL ENGINE BUSINESS

The small gas turbine engine business is usually considered to consist of engines having power levels up to the range of 2000-5000 hp or lb thrust, in contrast to the large jet and fan engines

used on fighter and transport aircraft, which may be ten times larger. Small engines are acknowledged to have fundamental problems of small scale whereby the higher efficiencies of large engines cannot be achieved. The small gas turbine alone has a wider range of military applications than large engines, which are generally developed for aircraft propulsion, with derivatives applied in limited numbers to marine applications. In addition, government funding levels for technology have been much lower in the small engine area since the mission or economic payoff is often not as great as in large engine applications.

For purposes of this study, the small engine business can be divided into four separate categories, each of which is unique and warrants the development of specialized engines. No manufacturer is dominant in all these markets, and few even try to compete in more than two. The categories are:

*MAN-RATED ENGINES-Used in helicopters and fixed-wing aircraft, the largest and best known applications.

*EXPENDABLE ENGINES-Used in tactical and strategic cruise missiles and target drones.

*AUXILIARY POWER UNITS-Airborne and ground, typically the smallest engines, often under 100-200 hp, and cost sensitive.

*GROUND VEHICLE AND MARINE ENGINES-Used in the Army heavy combat vehicles, and for marine primary and housekeeping power. Part-load fuel consumption is important and requires regenerative cycles for vehicles.

E. REQUIREMENTS FOR TECHNOLOGY DEMONSTRATION

All engine technology and development groups agreed on the need for engine demonstration programs for worthwhile improvements in performance. What "worthwhile" means depends on the application, cost, and the mission payoff. Small incremental

changes, improvements in current engines, for example, are feasible without demonstration. In general, some level of performance is always achievable without a technology demonstration; by setting modest goals, Full Scale Engineering Development (FSED) can be entered with the technology in hand. However, many turbine applications have high propulsion performance payoffs; this warrants advancing the level of technology. There is a level of performance that is easily achievable with the technology in hand and performance that is clearly not achievable with the foreseeable technology. If the payoff from improved performance is great, it is worthwhile to enter this region to establish just how far the technology can be pushed; this is the purpose of a technology demonstrator. A follow-on systems demonstrator may then be required to develop the confidence necessary to commit to a cost, performance, and schedule in FSED.

The discussions with engine groups also made clear that there is difficulty in justifying technology demonstration programs without an application and mission in sight. It would be useful to make clear that exploratory and advanced development, specifically up through 6.3A, is intended to provide information; development from 6.3B onwards is directed toward design of a specific engine. As useful as this may be in theory, in practice little exploratory or advanced development work meets this definition precisely, for two reasons: (1) the difficulty of funding a program without a defined end use, and (2) the agencies that are responsible for R&D generally serve a single user and concentrate on work that will be most useful to that user.

F. RANGE OF APPLICABILITY OF 6.3A DEMONSTRATORS

Figure S-1 graphically represents an idealized engine research and development process. In the figure, the farther a

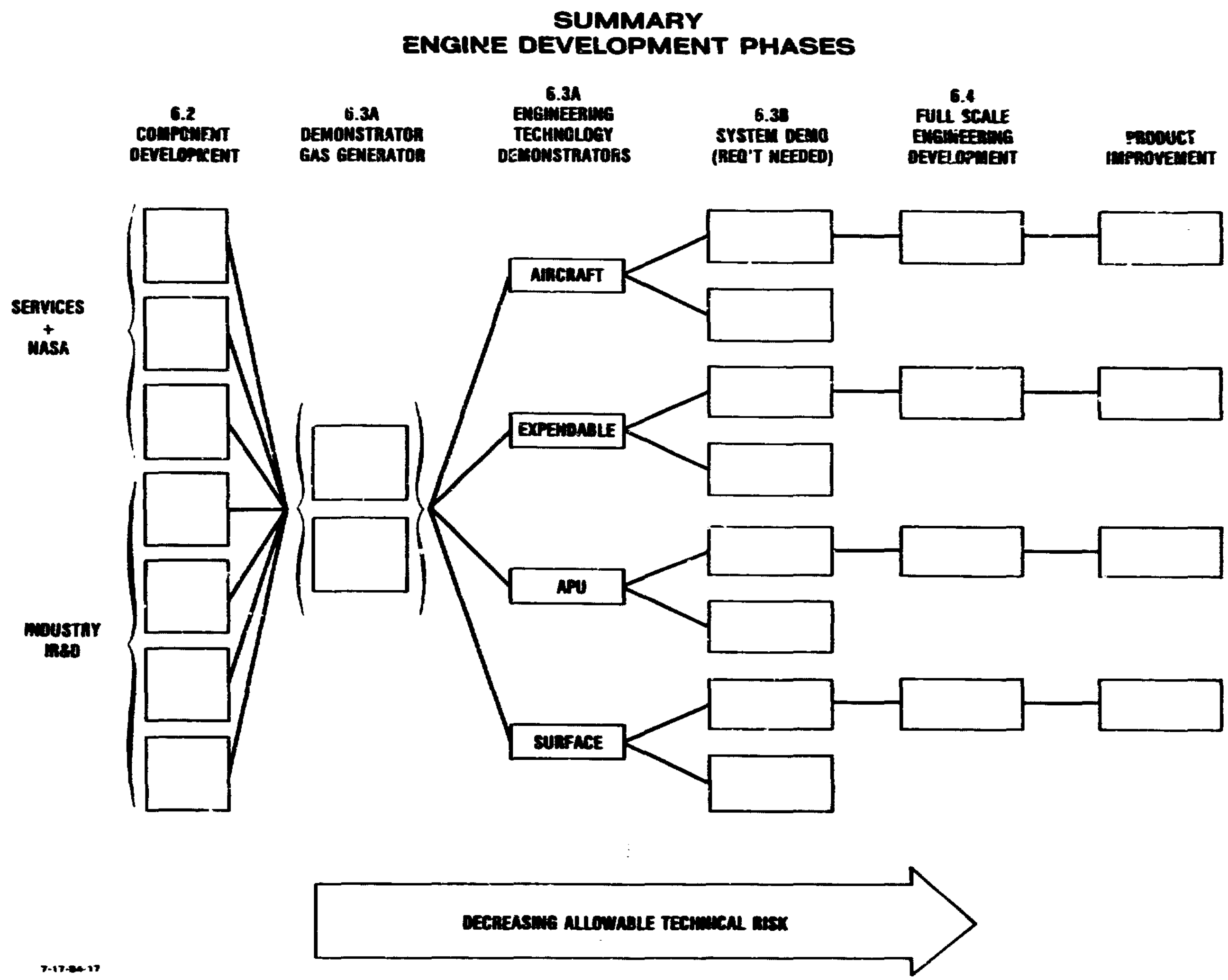

FIGURE S-1. A graphical representation of an idealized generalized development process for gas turbine engines. As the process moves from left to right the specificity of the development increases, the details of the end use become increasingly important, and the allowable technical risk decreases.

program is to the left, the more universal is its applicability. The programs to the right are very application specific. 6.3A programs are the rightmost programs that are not yet application specific, yet they are close to an actual running engine. The demonstrator engines funded under this line item may be complete engines, a gas generator, or an operable core engine. It would be highly desirable for the demonstrators funded under 6.3A to have universal application. What generally happens is that demonstrators are funded by agencies which have a particular mission requirement and the demonstrators are oriented toward a general, if not a specific, application. For example, potential aeronautical applications will emphasize lightweight designs, while vehicular applications may be heavier but of a cycle that is applicable to regeneration. Some aspects of these demonstrators have practical application to other areas, but other aspects do not. In general the aerodynamic design aspects and the rotating machinery may be more applicable to a range of end uses than might the external structure. The knowledge which permits high pressure ratio per stage with good efficiency is almost universally applicable to aircraft, vehicular, and expendable engines, although the optimization point for satisfying mission requirements may vary. The casing structure will vary, and therefore the method of controlling rotor tip clearances will be different. The bearing and lube systems will probably be different for short-life engines. Single-can combustors may be preferred for vehicular engines. The provision for a through shaft is very important for helicopter engines, fan, and two-spool engines, while it may be undesirable for marine or vehicular engines. It is clear that much technology is transferable across application areas, but some is not. A demonstrator which is supported by an agency interested in a specific application inevitably provides more information towards that application area; indeed, in some cases it may provide enough information that

a 6.3B application-specific demonstrator may not be necessary before entering the 6.4 program with sufficient confidence of making the desired schedule, performance, and cost.

Demonstrators which are core engines usually address high-temperature technology and perhaps high pressure ratio per stage in a high spool. These technologies may be transferable to other application areas if the size is not too much different, since scaling is practical over a reasonable scale (especially when scaling). These demonstrators usually require a supplemental program of low spools or fan spools before a 6.4 program could be entered with confidence.

Another demonstrator area that may have wide applicability is diagnostics capability. This is gaining importance in new engines to reduce the logistics support requirements. It would appear that the microprocessors and sensors necessary for diagnostic systems would have wide applicability. New materials may also have wide applicability, although some new turbine materials requiring coatings may be better suited to short-life expendable engines until more experience is gained. Also, some applications need materials with good low cycle fatigue (LCF) life, while corrosion resistance may be more important in others. The conclusion is that some aspects of demonstrator engines are widely useful, while others--particularly mechanical design details--are more often application dependent.

G. CRITERIA FOR JUDGING A DEMONSTRATION PROGRAM

The utility of an engine demonstrator program must be judged by several criteria. First is the overall system payoff due to

the expected engine performance improvements. For example, what are the improvements in tank performance, at constant cost, with a newer technology engine, or--perhaps a better measure for comparison--what is the reduction in cost of a tank with the same performance but using a newer technology propulsion system?

For new applications or missions, the mission probability must be considered; it is not worthwhile to develop a new engine that has enormous payoff only in a vehicle that is not very useful and unlikely to be built. There is admittedly some judgment involved in evaluating the probability of future missions, and official guidance alone is inadequate because the development time for a thoroughly new engine is greater than the length of time into the future for which guidance is reliable.

Any technology development program is more likely to meet the above criteria of mission payoff and mission probability if it is applicable to more than a single mission. This is especially important for small turbine engines because, as mentioned previously, some turbine applications have difficulty in alone justifying a technology development program but, taken together, the economic return would be reasonable if a single program could serve all their needs. Thus, range of applicability is an important criterion.

H. DEMONSTRATOR PROGRAM TIMING

The timeliness of a program must also be considered. On a gross scale, this is treated to some extent implicitly when calculating payoffs since the baseline for any comparison is what is available today. If any particular engine application has recently benefited from an engine development program, the additional gains from a new program will be relatively small; if the engine in hand is old, however, the baseline performance will be poor and the new engine developed by a program will appear

relatively more attractive. On a finer scale, one must anticipate the appearance of new missions and the obsolescence of inventory engines to determine whether an engine development program is justified now. An improved propulsion system may have high payoff and high mission probability, but if the mission will not appear until well into the next century, a program is not justified now. This can be contrasted with component improvement programs that have engines waiting for them.

The timing requirements of a technology development or demonstration program are less clear-cut. Technology programs funded under 6.3A are not intended to be designated for particular applications; it is necessarily more difficult, then, to relate the timing requirements of the program to the end application.

The criteria cited thus far for judging the utility of a program look principally at the mission. The program, on the other hand, will be concerned with developing or improving engine technology. The mission payoff is calculated from engine performance improvements that, in turn, derive from advances in technology. Engine performance depends on improvements in, for example, compressor pressure ratio and efficiencies that require higher tip speeds and lower tip clearances. These are achieved by the development of new materials and designs. Some estimate must be made of the likelihood that the required technology advances--in materials, for example--are possible with a program of limited cost.

I. CONCLUSIONS

The man-rated engine category has a need for a small engine technology program in the 500 hp class. The current inventory of engines in this class are of old design, and new technology demonstration programs are required. The forthcoming LHX engine and the existing T700 will cover the power range of 1200 hp and above.

Expendable engines are required for new cruise missiles. The payoff from engine performance is large for strategic cruise missiles. The required engines will probably be about 600-1000 pounds thrust, not too very different in size from the 500 hp helicopter engine, so scaling between the two sizes should be feasible.

The future requirements for APUs are not defined. A possible new mission is for high-altitude restart of fighter aircraft. This would require an APU of 400 hp, perhaps higher. Such a requirement would increase the payoff due to improved performance; at present, APUs are only a percent or two of the power of fighter engines and of the payload of transports, so vehicle performance is insensitive to APU performance. As the power required goes up, the sensitivity increases and payoff from improved performance increases. There is also a large potential need for small APUs for tanks and helicopters.

The next land-vehicle turbine engine will most likely be for a main battle tank. This need is being anticipated by the AIPS program. It is possible that future light combat vehicles, such as infantry vehicles, will be powered by turbines. Further study and system modeling is required to determine whether this is worthwhile. If so, component technology demonstration programs to support the land vehicle mission should be begun, because combat vehicle engines have many unique components.

J. RECOMMENDATIONS

Each of the categories has a need or potential need for a new engine in roughly the same size class. The relative timing requirements for each of the engine categories and the direction of technology transfer from one category to another suggest the following overall approach to technology support for small engines:

1. Concentrate on the size range of 500 hp for all categories to encourage maximum technical cross fertilization.

2. Begin a technology demonstration, probably a gas generator, for a future strategic cruise missile. The primary performance goal will be improved thrust specific fuel consumption. This technology demonstrator should encourage the use of new materials. Some possible materials, such as ceramics and coated carbon-carbon, have not yet been adequately demonstrated in rotating machinery in an engine environment. The limited life required of a cruise missile engine makes it an ideal first application for new materials. These materials may later find application in other engines.

3. Begin component technology demonstrators in the 500 hp size. This work may be tilted toward eventual application in a 500 hp helicopter engine. However, many possible components--for example, a high-temperature radial turbine (using either cooling or high-temperature materials--could benefit a variety of applications in this size. Coordinate the component development to allow the possibility of testing them in the gas generator in item 2.

   The increase in performance required to justify a new helicopter engine development program is large, and therefore the helicopter component programs should be aggressive. Novel solutions--for example, ceramic or carbon-carbon turbines--should at least be considered.

4. Conduct a review of the utility of turbine propulsion in lighter (30 tons) combat vehicles (much analysis has already been conducted). If the results are promising, begin component work peculiar to land vehicles (for

example, air cleaners) and to this size range (for example, regenerators). Plan on using hot section materials characterized in item 2 and rotating machinery technology developed in item 3 above.

5. Await definition of future APU requirements. When the need is clear, FSED can be entered without a preceding technology demonstration program specifically directed toward APUs unless very advanced technology is clearly needed to satisfy mission requirements. A new military APU developed with technology now in hand could be better than existing APUs. Technology developed in each of the above areas can be applied to APUs without separate demonstration if applied conservatively.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

This paper reports the results of a study conducted for the Office of the Deputy Under Secretary of Defense (Research and Advanced Technology, Military Systems Technology). The study examines the nature of the small gas turbine development process, identifies gaps between programs and probable future needs, and makes recommendations on near-term turbine engine research. The objective was to examine the extent to which the varying development needs for turbine engines can be met by a single demonstration program, or only a few, that develop the technologies common to turbine engines and would benefit all turbine applications.

Small gas turbine engines have a variety of applications in the military. Cruise missiles, tanks, helicopters, auxiliary power units, and ground and mobile electric power are applications for small turbine engines. For some of these applications, turbines are currently the only power plant used in military systems. This breadth of application and their great utility make turbine engine development important, but at the same time the turbine engine development process tends to be fragmented because of the number of turbine applications. Small turbine technology has not, therefore, advanced overall as quickly as comparable technology in large aircraft turbines. In addition, small turbines suffer performance penalties that are an unavoidable physical consequence of their smallness.

Turbine engines optimized for different applications have similarities as well as differences. In many small turbine engine applications, improvements in performance have a lower payoff than in large turbines or the total number of units may be small. It is therefore often difficult to justify economically an expensive large technology demonstration program for many engine applications individually; however, perhaps taken together the collective payoff and number of units could, in principle, justify the expense of a shared technology demonstation program. The study explores how engine technology development can be shared among the different end engine applications.

B. SCOPE

"Small" shall here describe any turbine less than about 2000 hp or equivalent size thrust engines. This is not a sharp cutoff, and it is recognized that as turbine inlet temperatures increase and pressure ratios go up, the components of the highest spool become smaller. Because of this, as technology improves the problems of smallness appear in ever larger engines. No restriction is placed on applications considered for small turbines. There are the several existing applications mentioned previously and some additional ones may appear in the future; for example, turbines could someday power armored personnel carriers and infantry fighting vehicles as well as tanks.

C. APPROACH

1. Visits and Observations

The first task of the study was to survey ongoing engine technology programs and the services' perception of needs by visiting the service laboratories responsible for propulsion research. In addition, to collect the views of industry (where

the majority of research and virtually all development actually take place), eight U.S. manufacturers of small gas turbines were visited. Table 1 lists these groups.

Table 1. GROUPS VISITED DURING SMALL GAS TURBINE STUDY

<u>Manufacturers Visited</u>

Allison Gas Turbine Operation
AVCO-Lycoming Division
Garrett Turbine Engine Company
General Electric Company
Solar Turbines, Inc.
Teledyne CAE
United Technologies, Pratt and Whitney
Williams International

<u>Government Agencies Visited</u>

Army Materiel Development and Readiness Command
Army Tank and Automotive Command
Army Belvoir R&D Center
Army Aviation Lab, Ft. Eustis
Naval Sea Systems Command
Navy Aero Technology Office
Naval Air Propulsion Center
Air Force Aero Propulsion Lab, Wright-Patterson AFB

During the course of discussions with government and industry research groups some facts, views, and opinions consistently came forward and are worth repeating here. The first was that engine demonstration programs remain essential. The hypothetical question was asked whether, with advanced computerized analytical capabilities, the need for a demonstration may be reduced until eventually a first engine design could be developed based only on

a complete characterization of components and a thorough understanding of the physics. All groups agreed that this capability was not foreseeable and that demonstation programs will remain essential for worthwhile improvements in fielded technology.

This statement has a hidden implication about the degree of improvement that is worthwhile. What "worthwhile" means depends on the application and the mission payoff. Small incremental changes--improvements in current engines, for example--are feasible without technology demonstration. Some level of performance is always achievable without a technology demonstration; by setting modest goals FSED can be entered with technology in hand. However, many turbine applications have high propulsion performance payoffs. Furthermore, there is a zone of uncertainty between what is easily achievable with technology in hand and performance that is clearly not achievable with foreseeable technology. If the payoff from improved performance is great, then it is worthwhile to enter this zone, to establish just how far the technology can be pushed; this is the purpose of a technology demonstration. (This may then be followed by a systems demonstrator that allows entering FSED with confidence of achieving a planned cost, performance, and schedule.)

In addition to the strictly technical requirements for demonstrators, there are programmatic requirements that demonstrators fulfill; they serve as clear-cut milestones that must be passed before the next and typically more expensive development phase is entered.

Another point was that the Independent Research and Development (IR&D) funding by engine companies is significantly larger than the direct government funding. The relative amount varies by company--from government-directed funding dominant to IR&D funding dominant--but averaged over the industry the IR&D is about three to five times direct government funding. This means that the government has little direct control over the majority of

technology funds, although most industry IR&D is directed toward development, not research. The other side of the IR&D coin is that there may be an indirect multiplier of directed government funding if industry can be encouraged to spend its IR&D funds in support of programs selected by the government for direct support.

A point that came forward very clearly, although not explicitly, is that companies are reluctant to accept government funding in many technology areas because of their desire to protect proprietary data. This limits the ways in which government can effectively support R&D efforts. A particular example is computer codes; companies may get and use general codes -- calculating thermodynamics properties, for example -- from the outside. Others, such as design codes developed in-house, are closely held, and companies would often not use such codes that had been developed out of house even if they were available.

A related problem is that the overall strategic commercial interests of the engine companies are not often identical to the interests of the government. Specifically, the government benefits by advancing the state of technology across the industry as a whole, while each company benefits by advancing the state of technology over which it maintains proprietary control. In cases where a single company has control of a particular type of technology market area, the interests of the company are not served by government-funded R&D efforts because competitors will use that support to enter the technical or market area which the company previously had to itself. Under such circumstances, it is to be expected that proposals for government research programs will be met by a notable lack of enthusiasm in some quarters.

Materials research is excluded from the above caveats by the small companies. The development and characterization of new materials is such a long and expensive process that the small

companies cannot afford it. Each seemed to recognize that it could not make useful progress alone and that an equitable means of sharing materials information would be of benefit to all. The two companies that manufacture primarily large engines are able to support in-house materials programs and, although these companies would not be as dependent on government support, they might be appropriate places to carry out the government programs; in this case, the small companies emphasized, the government must be rigorous in assuring that the materials information got out into the community of small companies.

Each of the government and industry groups expressed concern about increasing foreign competition in the small engine business. While it is true that competition is increasing, this is not necessarily a concern of the Department of Defense; only if foreign competition erodes the American industrial base to the point that our foreseeable military needs cannot be met, or if the industrial and technical capabilities of potential enemies presents a military threat, is it then of DoD concern. It appears that several foreign governments want to develop an engine manufacturing capability within their countries. The reason that they start with small engines it that the buy-in costs for developing large engine manufacturing capability appear substantial even for a government, and even then the market is very competitive. By elimination, then, small engines are the only reasonable way to break into the turbine engine world market. This can have a greater than expected influence on markets because, in many countries, there is only one engine manufacturer which may enjoy some degree of official or unofficial status and support from the government. This support will typically include, at the least, sole access to that government's military sales. In this way, not only is a new engine competing on the world market, but also a nation's market has simultaneously been lost to American companies.

All military service and industry engine groups would welcome early, clear statements of mission needs. This problem has a programmatic side as well: it is difficult, during the budget process, to justify programs without a clearly defined end application. The better solution to the problem of vague future mission requirements is to convince those that determine budgets that the purpose of technology demonstration is to advance the state of technical capability which will be applicable to a broad range of possible future engines.

The final point to bring forward from discussions with engine groups became clear from comparing perspectives of the groups. The small turbine engine business seems to divide into four distinct market areas: (1) man-rated aircraft engines, (2) expendable engines, (3) auxiliary power units, and (4) ground vehicle engines. No company is dominant in more than two of the areas, and most participate prominently in only one area.

Like all markets, the market for small turbines is limited, and in some market areas the government is the sole customer. There is therefore every motivation for a company to expand into different markets since it is difficult to expand its current market.

This lack of diversity, in spite of expected benefits, suggests -- without speculating on how and why -- that there are four different types of business areas and four different categories of engines. This has important implications for the optimal way to allocate government RDT&E funds, the transfer of technology across market area boundaries, and the minimum number of demonstration programs that are useful. In discussions that follow, it is assumed that these market area divisions are real.

2. Criteria for Recommendations

The utility of an engine demonstrator program must be judged by several criteria. First is the overall system payoff due to

the expected engine performance improvements; for example, what are the improvements in tank performance, at constant cost, with a newer technology engine or, perhaps a better measure for comparison, what is the reduction in cost of a tank with the same performance but using a newer technology propulsion system? Also, for new applications or missions, the mission probability must be considered; it is not worthwhile to develop a new engine that has enormous payoff only in a vehicle that is not very useful and unlikely to be built. There is admittedly some judgment involved in evaluating the probability of future missions, and official guidance alone is inadequate because the development time for a thoroughly new engine is greater than the length of time into the future for which guidance is reliable. A conservative approach to the problem of mission probability that is adequate for many existing missions is to assume that the near future will be similar to the near past; that is to say that we shall have tanks, helicopters, and subsonic cruise missiles in the near future because we have them now, and it is plausible to extrapolate their missions into the near future. This approach automatically overlooks new missions, and more detailed analysis is required for an estimate of the probability of new mission applications--for example, turbine engines for armored personnel carriers or supersonic cruise missiles.

Any technology or development program is more likely to meet the above criteria of mission payoff and mission probability if it is applicable to more than a single mission. This is especially important for small turbine engines because, as mentioned previously, some turbine applications have difficulty in alone justifying a technology development program but, taken together, the economic return would be reasonable if a single program could serve all their needs. Thus, range of applicability is an important criterion.

The timeliness of a program must also be considered. On a gross scale, this is treated to some extent implicitly when

calculating payoffs since the base line for any comparison is what is available today. If any particular engine application has recently benefited from an engine development program, then the additional gains from a new program will be small; if the engine in hand is old, however, then the baseline performance will be poor and the new engine developed by a program will appear relatively more attractive. On a finer scale, one must anticipate the appearance of new missions and the obsolescence of inventory engines to determine whether an engine development program is justified now. An improved propulsion system may have high payoff and high mission probability, but if the mission will not appear until well into the next century, then a program specifically targeted for that mission may not yet be justified.

The timing requirements of a technology development or demonstration program are less clear-cut. Technology programs funded under 6.3A are not intended to be designated for a particular application; it is necessarily more difficult, then, to relate the timing requirements of the program to the end application.

Unfortunately, the question of timeliness also concerns money: engine technology programs are expensive and only a few can be funded at any given time. Because of this, a program may be warranted and an analysis of needs may suggest that it be started now, but if another program, already in place, is using all available funds, the new program can hope for little more than being next in line.

The criteria cited thus far for judging the utility of a program look principally at the mission. The program, on the other hand, will be concerned with developing or improving engine technology. The mission payoff is calculated from engine performance improvements that, in turn, derive from advances in technology. Engine performance depends on improvements in, for example, compressor pressure ratio and efficiencies that require higher tip speeds and lower tip clearances. These are achieved

by the development of new materials and designs. Some estimates must be made of the likelihood that the required technology advances--in materials, for example--are possible with a program of limited cost.

D. CHARACTERIZATION OF THE SMALL ENGINE BUSINESS

The small gas turbine engine business is usually considered to consist of engines having power levels less than 2000 hp or pounds thrust, in contrast to the large jet and fan engines used on fighter and transport aircraft, which may be ten times larger. Small engines are acknowledged to have fundamental problems of small scale whereby the good efficiencies of large engines cannot be achieved. Besides size differences, the small gas turbine has a wider range of military applications than large engines, which are generally developed for aircraft propulsion, with derivatives applied in limited numbers to ground and marine application. Also, government funding levels for technology have been much lower in the small engine area than in large engine applications.

The small engine business can be divided into four separate categories, each of which is unique and warrants the development of specialized engines. These categories are:

* **MAN-RATED ENGINES.** The man-rated turbine engine for helicopters and fixed-wing aircraft is probably the best known and largest market for small engines; the established disciplines for flight certification are recognized and not greatly different from large gas turbine practices. The largest military market is in helicopters, and the largest commercial market is in turboprop engines for fixed wing aircraft. There is a smaller military turbofan market for trainers.

* **EXPENDABLE ENGINES.** Tactical and strategic cruise missiles are distinguished by short design life and, being expendable, are never overhauled; target drone engines are also

in this category. The design and development philosophy must be quite different from long-life man-rated engines, and there is limited knowledge as to how to practically design a short-life engine. There is a common perception that expendable engines ought to be low in cost. This is difficult to support with quantitative economic analysis in many applications, especially in the case of strategic cruise missiles.

* **AUXILIARY POWER UNITS**, both airborne and ground. Auxiliary power units are typically the smallest shaft power engines, often being under 100-200 hp, and efficiency has not been as critical as low cost and reliability. Airborne APUs are widely used in commercial transport aircraft as well as military aircraft, and the use may be expected to expand; in the future, military requirements may become much more stringent, perhaps for continuous operations and with higher power requirements. Portable ground electrical power systems would be much more widely used if the acquisition cost were competitive with diesel engine systems.

* **GROUND VEHICLE AND MARINE.** Ground vehicle application of gas turbines was emphasized with the selection of a gas turbine to power the Army M1 battle tank. Ground vehicles are not as sensitive to engine weight as aircraft are, but low fuel consumption over a wide power range is very important; therefore, the vehicle engine incorporates a heat exchanger for exhaust heat recovery, at the expense of added engine weight and volume. The customer is a heavy-vehicle manufacturer, and the vehicle/engine integration is quite different from aircraft application.

The applications of small gas turbines involve different markets which may be quite different businesses from each other. While all eight U.S. turbine engine manufacturers claim to be in the small engine business, none of the eight manufacturers are involved heavily in all of the markets listed above. It is interesting to note that the number of basically different engines produced by each company is relatively small. Generally, the man-rated engines are both higher-cost engines and in larger production, giving this area the highest dollar volume and high interest to the industry.

II. THE ENGINE DEVELOPMENT PROCESS

A. GENERALIZED DEVELOPMENT PROCESS

The development of a new gas turbine engine, even a small engine, is a long and expensive process. Figure 1 illustrates the stages of a generalized, idealized development process. Not all, or even most, small engines will necessarily pass through each step explicitly, but each step will be present in some form, for example: even though the development of a gas generator may not be a separate program, a gas generator phase will be included in the development, probably as part of the engineering technology demonstrator. Where the gas generator program (to follow this particular example) is covered and how it is funded is not merely an administrative detail; it affects the nature of the technology development and demonstration process and the likelihood that technology developed with one application in mind will find its way to another application.

Going from left to right across the diagram, tracing the stages of engine development, each stage approaches closer to the final production engine. Each stage is more closely tied to a final design, flexibility is reduced, and typically the cost of each stage is greater than the last. As the program moves toward the right, the timetables become firmer and final missions and requirements become clearer. All of these things lead to a lowering of the acceptable level of risk as the program progresses; bold and innovative ideas must be tried out and proven on components before they will even be considered on gas generators, and the trend of accepting less risk continues to the

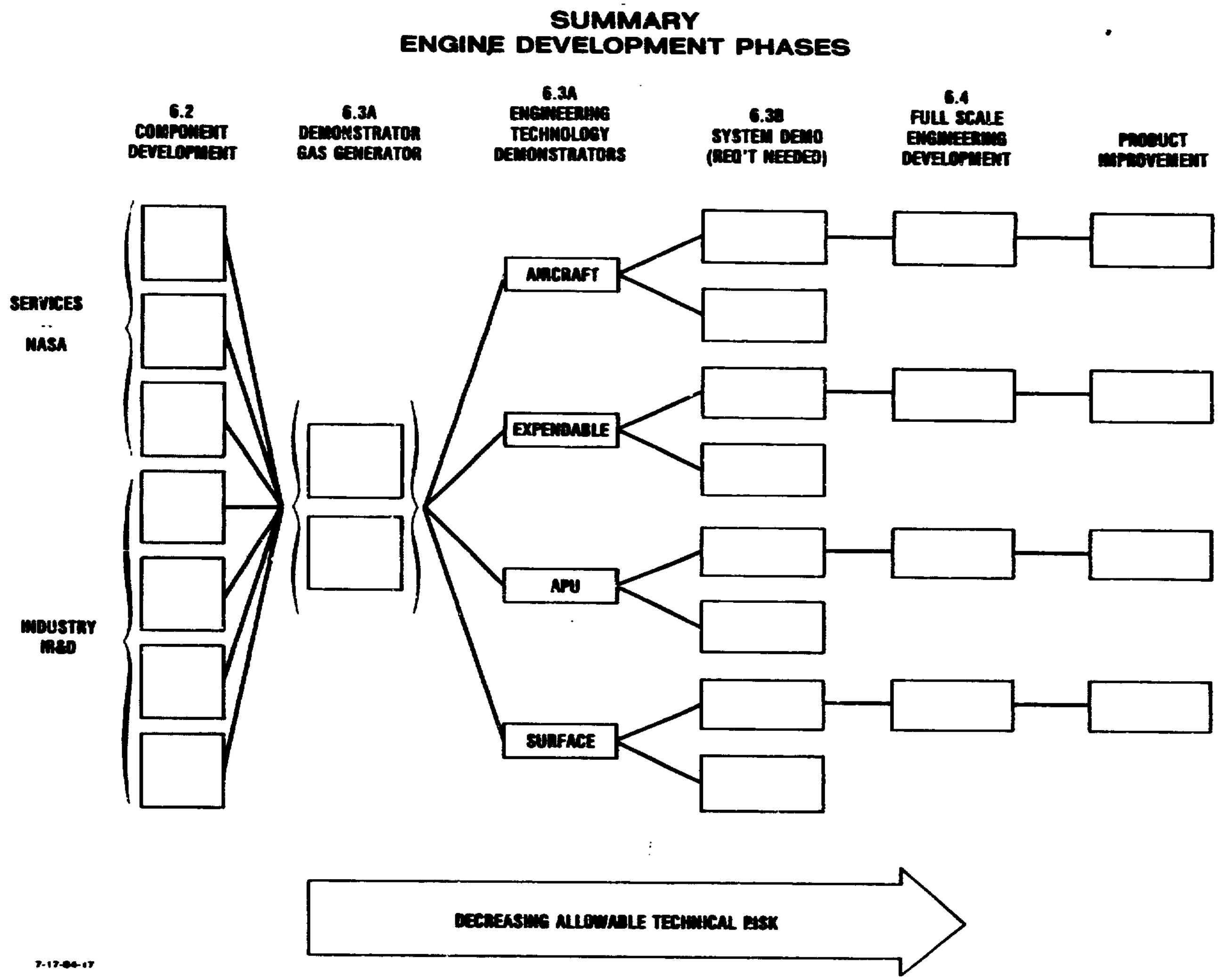

FIGURE 1. A graphical representation of an idealized generalized development process for gas turbine engines. As the process moves from left to right the specificity of the development increases, the details of the end use become increasingly important, and the allowable technical risk decreases.

right. In general, new technology is tried out toward the left up through 6.3A, and new designs of engines are worked out on the right from 6.3B on.

It was pointed out in the previous section that there seem to be four distinct small-engine businesses and that this implies that there are four small-engine categories. Toward the right-hand side of the figure, the design particulars of each engine application must be considered. For example, careful attention must be given to the design of air filters for ground vehicle engines; however, these will have unique application to ground vehicle engines in particular, not small turbines in general.

This study attempts to identify ways to advance the overall level of small turbine technology; these opportunities will tend to be found toward the left in the figure. In particular, up through 6.3A funding, technology programs are not intended exclusively for any specific application.

Technology areas that allow broad application are lightweight structure, high-temperature materials, improved aerodynamics (for example, to reduce the number of stages at constant efficiency), controls, and diagnostics. Some of the technology developments listed here will be part of a more comprehensive engine development program. This engine may clearly be a specific category--an expendable engine, for example--but some of the technology demonstrated will be applicable to all engine categories. The engine development process may be 10-15 years from the beginning of component technology development until these components find their way into Full Scale Engineering Development and production of an engine. An additional 1-2 years may be required to acquire machine tools and special tooling and to verify the production process, depending on procurement decision timing.

The process which has evolved is one involving a series of steps, each one of which is more directly associated with the end item, each of which is described in greater detail below.

1. Components

The earliest development phase is usually rather broad-based with multiple approaches directed to the individual components of an engine, such as compressors, combustors, turbines, bearings, and so on; it may also involve materials, fuels, and lubricant development. These programs are typically funded by 6.2 RDT&E funds. The purpose of the component development is, for example, to provide information on a new compressor design or a new turbine material. There may be no particular end use in sight, only a generic application. When the component technology is understood and validated in a test rig, it is possible to enter the demonstrator engine phase using the information generated in the component demonstration program.

2. Demonstrators

A technology demonstrator engine is either a complete engine, a gas generator, (e.g., shaft turbine without the power turbine) or an operable core engine (e.g., inner spool or high-pressure spool of a turbofan or multispool engine) which is used for the purpose of validating the status of some new technology or set of components in an actual engine environment. By this stage of technology demonstration the development process is usually associated with a particular category of engine but not a particular application. That is, a technology demonstration will often be identifiable as a man-rated engine, for example, as opposed to an expendable engine, but not necessarily identified with a particular helicopter or turboprop application. This is almost inevitable, if not for technical reasons, then for administrative reasons; given that an agency responsible for a

particular mission is funding the program and the work is being carried out at an engine company with a particular market, it is difficult to avoid having the technology demonstrator fashioned toward a particular engine category.

Following the technology demonstration phase is the system demonstration phase, which is tied to a particular end application. The purpose of this demonstrator phase is to provide assurance that engineering details are sufficiently understood so that the FSED phase can be entered with confidence of achieving a predicted performance to a predicted schedule and cost. In practice the distinction between technology and systems demonstrations is not always so clear. In earlier states of technology development, it is common to utilize an existing engine to test a new component, material, or manufacturing process, which then becomes a demonstrator engine. In the case of a completely new engine, it may be excessively expensive or complex to initially fabricate and test the complete engine, and only the core or gas generator will be demonstrated. In cases where important technology affects the entire engine, such as control systems, inlet systems, regenerators, low spools, etc., a complete demonstrator engine, even for technology demonstration, must be tested. However, in cases where the demonstrator engine program is undertaken for the purpose of validating that a specific system requirement can be fulfilled, the program is supported by 6.3B RDT&E funding; in all other cases, it is supported by 6.3A funding.

3. Full Scale Engineering Development

The Full Scale Engineering Development is a major effort, usually involving four or more years and 7,000-10,000 in-house development test hours, plus some flight or field testing in a typical application. The cost may be at least 5 times that of the demonstrator engine phase, perhaps hundreds of millions of

dollars, depending on size. Therefore, a completely new engine can usually only be justified infrequently, when the application demands are sufficiently large and important to warrant the large expenditure of time and money. This phase is supported by 6.4 RDT&E funds. Following the completion of FSED, the Government often funds programs to upgrade an existing engine for improvement in reliability, for instance, which may be funded by RDT&E or other funds.

4. Discussion

While the foregoing describes the classic development process, it also appears that there is not and should not be a stereotyped development process for each engine. In general, once a mission and a requirement are defined, the time is so short that it is probably more productive to support complete engine demonstrators (a 6.3B type program) from which the FSED contractor can be selected. On the other hand, at all times improved propulsion technology is useful across a range of applications. In this case, generic technology demonstrators, such as an ATEGG, consisting only of a gas generator or high spool, would seem to be an important phase, allowing more advanced technology to be incorporated into any subsequent 6.3B demo and FSED engine. Sizing of the spool demo is not critical, and it may be desirable to work on relatively small sizes for economics of both time and money; the scaling upwards is practical within limits. It may be possible to skip the 6.3B phase if the technology required is sufficiently validated to permit entering FSED with confidence. This may be possible in cases where a new engine is needed but the performance required of the system does not stress the current state of technology and engine design. (Such a case could be, for example, a ground power unit with modest performance similar to existing engines but of a different size.)

The development process is most standardized for man-rated aircraft propulsion, and the above paragraphs are most applicable to this engine category. The process varies considerably for each of the engine categories. For years, many APUs have been evolutions of previous models or adaptations of other engines, and have not even utilized the demonstrator phase of development. For example, among the most common of APUs is the Solar T62; it was originally developed for a one-man helicopter application before today's demonstrator process was developed. Ground electrical power sets and marine engines have largely been derived from engines developed for other purposes. For example, the LM2500 marine engine is an adapted aircraft engine. Ground vehicle engine developments undergo significantly different qualification procedures and requirements for technology validation of complete engines or even complete power packages and may involve different engine types (piston and turbine). The qualification procedures for expendable engines are very different. The specifics of the development of each engine category are discussed in more detail in the following sections.

B. SPECIFICS OF DEVELOPMENT PROCESS FOR MAN-RATED AIRCRAFT ENGINES

Man-rated military engines in the size range considered find their principal application in helicopters and a much smaller market in turbofans for military trainers. The civilian market for turboprops and turbojets engines for commuter airplanes is as large as the military market.

The man-rated aircraft engine development process is usually the most comprehensive of engine developments. This is because aircraft engines must be very lightweight and efficient for aircraft to be productive, and performance has a high military payoff. The highest level of technology is therefore demanded.

Also, because flight safety is of overriding importance, the FSED phase of development is the most formally defined of all engines, is very lengthy and intense, and culminates in officially reviewed and approved qualification tests.

The large military payoff from increased performance in aircraft engines has caused emphasis to be placed on technology development, starting with 6.2 RDT&E funded component technology programs. Typically, multiple approaches with multiple contractors are supported on each major engine component, such as compressor, combustor, turbine, controls, and bearings, as well as associated areas of fuels, lubricants, and materials.

The demonstrator engine phases are historically more heavily emphasized in the aircraft engine development process than others. All companies and services agree on the necessity for these phases. Component tests are considered simulations only, and the components must be tested in a demonstrator to be in the right environment. The technology demonstrator can be a complete engine, a gas generator, or an operable core engine. In some cases, the technology demonstrator could evolve through all phases from core or gas generator to engine. These programs are supported by 6.3A RDT&E funds.

In the case where the program is undertaken for the purpose of validating that a particular systems requirement can be fulfilled, the program is a system demonstration supported by 6.3B RDT&E funds. In most cases, all the possible demonstrator phases are not conducted, at least not as separately established programs. The final result of the demonstrator phases is that the technology is sufficiently validated to permit entering the 6.4 FSED phase with confidence of achieving a specified performance, schedule, and cost.

C. SPECIFICS OF DEVELOPMENT PROCESS FOR EXPENDABLE ENGINES

Expendable or short-life engines power cruise missiles and target drones for periods of a few hours down to a few minutes. The engines can therefore have design lifetimes of just tens of hours. This allows expendable engines to stretch technology a bit further than man-rated engines. For example, a short-life engine could plausibly operate at significantly higher temperatures than a long-life man-rated engine which uses the same material. Because of this, the development process will be at least slightly, and in some cases substantially, different from that of man-rated engines. Only the military have a requirement for expendable engines and this is important for funding of the technology.

There have not been many expendable engines developed, and therefore there is not a well-established uniform process for their development and qualification. Past target drones and strategic cruise missiles have used engines developed for other purposes and adapted to the application. Tactical missiles using jet engines (for example, the Harpoon) have had a special engine developed for the application. Because future tactical and strategic cruise missiles are apt to have much more stringent performance requirements, it is likely that special engines will be developed, and that a process much like that described for man-rated engines will be necessary. The major difference in the process has to do with the short engine-life requirements and the lack of overhaul requirements, while a high level of reliability is still required. The short design life and limited overhaul capability does not always permit accumulation of large numbers of test hours and disassembly for inspection during the process of developing performance and reliability. It is likely that larger numbers of engines will be utilized in future expendable engine development than in man-rated engines even though the total

accumulation of development test hours may be much less. The qualification procedures are not as well established for expendable engines as in man-rated engines, and qualification tests tend to be established for each engine as a function of the specific application, although the qualification is still a formal process.

It is likely that component technology programs will be much more important for future cruise missile engines as very high performance levels may be required. The design practices for very short-life at maximum performance are not yet well established, and special starting systems and short-life lubrication systems may be unique.

Technology demonstration programs for short-life engines may prove valuable in the overall process of developing new materials. After experience has been gained with a material in fabrication and operation in short-life engines, the material may evolve into use in high-performance man-rated engines.

D. SPECIFICS OF DEVELOPMENT PROCESS FOR LAND VEHICLE ENGINES

While engines for ground combat vehicles have been developed and used for many years, the use of gas turbine engines in combat vehicles is quite new, there being only one example in production--the AGT1500 engine in the M1 battle tank. Therefore, the development process for vehicle gas turbines has not undergone much evolution, except in modifing the process evolved from typical diesel engine development for vehicles.

There is not the same history of intense component development of turbine components in the land vehicle area as there is in aviation. It is not that the performance of high-technology engines is not desired; it is because the technology developed for small aircraft engines has been utilized, particularly for turbo-

machinery, while the limited funding available for component technology has been directed to the unique componentry of the vehicle engine (i.e., regenerators, air filters, etc.).

In the past, there were no identified demonstrator engine phases of development; however, there were analogous programs of competing air-cooled versus liquid-cooled diesel engines which were really demonstrators, although not identified as such. There was no demonstrator phase in the AGT1500 development process, just a very long and difficult development often hindered by lack of adequate technology as well as a lack of funding or specified application. (This may demonstrate by counterexample the value of technology demonstrations.)

At this time, it appears that the Army is embarked on a complete new tank propulsion system demonstrator program called the Advanced Integrated Propulsion System (AIPS), sized for heavy tanks. The program involves two competing contractors with different approaches (turbine and reciprocating engine) and will result in a demonstration of the complete propulsion package including engine, transmission, air filter, controls, final drive, fuel system, and auxiliary power system, to be finally tested in an Army facility. The development process for new combat vehicle engines has continued to evolve over the years, and it now appears that greater emphasis is being applied to demonstration of the overall integration of new technology propulsion components as a package before FSED is entered. Although the entire engine is demonstrated, these are technology demonstrations (if they are very successful, it may be possible to go directly to FSED).

The qualification of combat vehicle engines is dependent on the specific end item application. The engine-and-propulsion package is qualified for production as a part of the total vehicle system and is approved for production when the total vehicle system is type classified and approved for production. This FSED process does involve a large number of engine test hours both on a

dynamometer and in representative test vehicles, and test procedures have evolved which represent service operation. Considerable mileage is accumulated on the vehicle system before it is verified as acceptable for service use.

Marine engines are included in this category inasmuch as they are nonflying main propulsion engines. In general, the marine requirement is not sufficient to warrant the development of special engines due to the small quantities involved and the cost of developing a new engine. Modified engines from other applications satisfy marine propulsion requirements. Specifically, the process of 'marinizing' aircraft derivative engines has evolved to satisfy marine requirements. This usually involves the substitution of materials to better withstand the salt atmosphere and higher sulfur and other contaminants of marine diesel fuels and may involve the conversion of a jet engine to a shaft power engine. While not necessarily resulting in optimum engines for the application, the requirement is satisfied at an acceptable development cost without undue penalties. It does not appear at this time that the process for obtaining marine engines will change even though the marine duty cycle would tend to favor engines having better part-load fuel consumption than derivatives of simple-cycle aircraft engines.

E. SPECIFICS OF DEVELOPMENT PROCESS FOR AUXILIARY POWER UNITS

Most APUs now in service have evolved over many years and did not undergo the development process from component technology through demonstrator to FSED. There have not been technology programs to develop new APUs for the military in recent years. APUs have been developed commercially for civilian aircraft because there is an important requirement for both starting and environmental control, and the market is large. Although the largest market for APUs has been in aircraft, there may be a future market in combat vehicles, which have increasing amounts of

housekeeping power requirements. Also grouped in this category are mobile electric power sets, which are widely used in the military for portable electrical power.

APUs for aircraft application also must meet requirements for flight safety; therefore, they also must satisfy formal requirements of qualification similar to man-rated aircraft. While the developments have been evolutionary for many years, there are potential new aircraft requirements which have performance payoffs high enough to justify much improved technology. For example, future fighters may have high-altitude restart requirements. This could necessitate a development process from component technology through technology demonstrator and system demonstration to FSED, similar to man-rated engine developments. If the APU becomes a more vital part of an integrated aircraft system, it is probable that the APU, like the main engine, must validate its performance and practicality in a system demonstator before the aircraft system can be committed to development.

If combat or tactical ground vehicles become important users of APUs, there may be new requirements for units smaller than the typical aircraft APU, in which low cost may become a major requirement. In this case, some new technology may be necessary which would be best developed by the complete component-through-demonstrators-to-FSED process, although the qualification would probably be as part of the vehicle qualification, similar to the land-vehicle engine development process.

In the case of mobile electric power, it seems unlikely that general-purpose sets can justify special new engine developments; therefore, it is more likely that the process of adapting turbine engines from other developments will continue to be the major development process in this area.

III. EVALUATION OF DEMONSTRATOR PROGRAM OPTIONS

A. MAN-RATED ENGINES

1. Current Programs and Future Mission Probability

The dominant military application of man-rated aircraft turbine engines in the size range considered here is for helicopters; the Army, therefore, has most of the man-rated programs. There is a smaller military requirement for turboprops and a substantial civilian turboprop market. (This civilian market can benefit the military because an expanded market can reduce unit costs.) There is a small military market for turbofans for trainers just beyond the engine size limits set out for this study.

There are two ongoing or recent demonstration programs for man-rated engines. The Modern Technology Demonstrator Engine (MTDE) is a 5000 hp shaft engine demonstrator and somewhat outside the present definition of "small." It is not committed to a particular application but is of the size appropriate to turboprops, heavy helicopters, and the JVX. The Advanced Technology Demonstrator Engine (ATDE) is an 800 hp turboshaft demonstration engine. It is of a size suitable for medium-weight helicopters. Although the ATDE is not designated as the demonstration engine for the Light Helicopter Experimental (LHX), the difference in size between 800 and 1200 hp is within acceptable scaling range, and engines developed from the ATDE program are obvious candidates, as are derivatives of some existing engines.

In between the 800 hp ATDE and the 5000 hp MTDE sizes there are no ongoing demonstration programs. The Army is about to initiate a program to competitively select a contractor to enter FSED for the 1200 hp LHX engine. Contractors will enter FSED planning to use only technology that has been validated; this means that the components and configurations must have been proven in a demonstrator such as the ATDE, in component development, or in an existing engine. This program is intended to result in a new technology engine at the end of the decade.

The 1500 hp T700 falls in this range between the ATDE and MTDE. The T700 is fairly new and of good performance. Even so, given the importance of the T700 to the Army and the very long development times for new engines, it will not be long before the first steps in the development to the T700 follow-on need to be considered. The T700, like most engines, is increasing in power incrementally through various component improvements. This nominal 1500 hp is fast approaching 2000 hp and will probably exceed that before the middle to late 1990s when the follow-on will be ready. If a new 1500 hp engine is needed, that slot can be filled in the short term by the expected growth in the new LHX engine. This degree of power growth is well within historical limits and is, in fact, a specified capability for the LHX engine.

It seems that the stated requirements and expected general propulsion needs are well covered above 1000 hp. There is no particular ongoing or planned future effort below 1000 hp, and no such military aircraft requirement is known to be imminent; however, there are many light observation and utility helicopters now in the Army inventory (over 5000 UHs and AH-1s and over 2000 OH-6s and OH-58s). The replacement of these small helicopters is being used to help justify the LHX; it seems unlikely, however, that a 2400 hp LHX will be an economical replacement for current helicopters in the 500 hp class such as the OH-6 and OH-58 if observation helicopters are maintained in anything like their present number.

It is possible that as soon as the LHX program is irrevocably established, a stated need for a new 500 hp helicopter will appear. It must be emphasized that the total development lead time for an engine may be 10-15 years, and there is a high probability of a future requirement for small scout or utility helicopters that cost much less than the LHX. Requirements sometimes materialize quickly as a result of some new threat or doctrine and are sometimes caused by military personnel changes. In order for requirements to be considered and studied for new small helicopters, it is necessary to conduct technology programs to permit realistic assessments of what may be feasible and the potential payoffs. Since the Army now owns and operates thousands of helicopters smaller than the LHX, it seems probable that a future small helicopter engine requirement will materialize. Unless some technology programs are initiated soon, it will not be possible to respond to a new helicopter requirement when it arises.

It appears that the most appropriate size of small shaft engine to cover potential future requirements would be the 500 hp class. An engine of this size would seem to satisfy new scout helicopter requirements as well as provide for the 1000 hp class as a twin in case a UH-1 sized replacement is sought.

There are no known potential military requirements for small man-rated jet or turboprop engines for fixed wing aircraft, although there is probably commercial interest in both a 500 hp turboprop and a shaft engine for helicopters. While there may not be adequate commercial incentive to develop future new-technology 500 hp engines, the commercial market would significantly benefit the military by providing a larger production and support base, which would reduce costs of engine ownership.

Inasmuch as the Army is now rather heavily funding aircraft engine programs in both the 6.3 and 6.4 areas, and the requirement for a 500 hp engine is in the future and as yet ill defined, it is

probable that the most realistic approach toward this objective is to initiate a series of component technology programs oriented toward 500 hp, with a view to entering a technology demonstrator engine program soon afterward.

There could be important benefits to both the APU field and the land combat vehicle field if technology were advanced in this size category, thereby increasing the overall significance of work in this area. These requirements will be discussed in more detail in the appropriate sections, but here it is pointed out that potential new fighter requirements for APUs may be in higher power than now in the region of up to 500 hp, and the potential requirements for land vehicles may be in smaller engines than now, down toward 500 hp.

2. Performance Payoff

An elementary analysis was made of the benefit to a small helicopter of the application of modern and future technology engines in the 500 hp class. The modern engine was considered to be the best technology which could enter FSED now, without demonstrator phase, and for the future technology five additional years of technology development were considered. First, the existing engine was replaced by the new engines, and the improvements in endurance, range, and payload were calculated. Then, the original endurance, range, and payload were maintained while a new helicopter, taking full advantage of the new engines' lighter weight and lower fuel consumption, was configured. This resulted in a smaller helicopter.

The results are shown in Table 2. It can be observed that the future technology yields approximately 50 percent gain in endurance, range, or payload when retrofitted to the existing airframe. What this is worth depends on the future mission

requirements. A new helicopter performing the original mission is smaller, offering considerable dollar savings when fleet operation over a number of years is assessed.

Table 2

	Current Hel/Eng	Best Current Technology	Future Technology
<u>Retrofitted Engines:</u>			
Helicopter TOGW	4,250	4,250	4,250
Additional Mission Time or;	-0-	.55 hrs	1.04 hrs
Additional Payload	-0-	120 lbs	190 lbs
<u>New Helicopter:</u>			
Equal Payload/Mission			
Helicopter TOGW		3,970	3,774
Airframe Structure Savings		$41,995	$71,431
Fuel Savings/Yr.		$ 2,205	$ 4,908
2,500 fleet 10 yr. Savings		$160 Mill.	$300 Mill.

Assumptions: 1 lb. Eng-Fuel Saved = 1 lb. Structure Saved

Structure Cost = $300/lb.

Fuel Cost = $1/gal.

Flying Hours = 40 hrs./mo.

However, the cost of a development program is also large; it will be measured in hundreds of millions of dollars. With the assumed fleet size, the lifetime payoff is not overwhelmingly larger than the probable cost of a development program. This is a result of a maturing engine technology. It suggests that new technology must be pursued aggressively. As the technology matures, the step in improvement in performance will be less with each development program, yet the development programs will remain roughly constant in cost. Eventually, the point is reached when the normal evolutionary, incremental improvements in aero-thermodynamics performance will not justify, in terms of mission payoffs, the cost of a development program. At that point, a new program can be justified only (1) if some revolutionary new technology can be incorporated, a new material, for example, or (2) if the cost of a development can be dramatically reduced, through computer-aided design, for example, or (3) if some new mission appears for which the payoff is greater, a very long range helicopter for example, or (4) if logistic advantages are great.

The savings are dominated by airframe costs, not fuel costs, so procurement is the most important number. Procurement numbers may be much greater than fleet size. (This is especially true if the helicopters see action, as was made clear in Vietnam.) Unfortunately, this is difficult to predict. The present fleet of small helicopters is about 2200 units, but several times that many have been procured. Perhaps all that can be stated safely is that the 2500 value for fleet size in Table 2 should perhaps be taken as a lower bound.

Similar calculations were carried out for a follow-on T700 engine. Again, best current-technology and future-technology engines were assumed. It is difficult to distinguish the best current-technology engine from the LHX engine in performance; moreover, the LHX engine performance is not a great deal better than the T700 performance. The LHX engine will have fewer parts, be simpler, more reliable, and so on, but these nonthermodynamic

performance benefits do not show up in this analysis. The future-technology engine assumes a 50% increase in pressure ratio and a 200°F increase in TIT.

For retrofit into an existing helicopter this yields an extra 20 minutes of mission time. For a redesigned helicopter this new engine technology, subject to the same assumptions used in the small helicopter calculation, yields a structural saving of $132,400 per airframe and a fuel saving of $9,100 per aircraft per year. Ten-year, 6000-aircraft, fleet savings equal $1.34 billion. It would seem that economically the higher payoff comes in starting a demonstrator program for an LHX engine follow-on. However, the LHX--which will replace the UH-1, the AH-1, and perhaps the UH-60 sized helicopters--will not be ready for replacement when such an engine is ready. This means that the aircraft structure savings are not available; only the fuel savings are realizable, and these amount to less than half the above savings, or $545 million. So the fuel savings would not even cover engine procurement costs. Both fuel cost and airframe cost are recovered in the case of the small helicopters if one assumes that the small helicopters, some of which are 30 years old, will need to be replaced in any case.

3. Technology Required for Postulated Future Helicopter Engines

In examining the potential helicopter improvement through advanced-technology engines, two levels of engine technology were established. The first level was that estimated to be the best technology which could be incorporated into an FSED phase now, not requiring a demonstrator phase. The second level was that best technology which could enter FSED in approximately 5 years if active component technology programs were entered now, followed by a technology demonstration, such that the engine could be qualified for production in approximately 10 years. The characteristics of the two engines are given in Table 3.

Table 3

	Best Current Technology	Future Technology
Compressor Pressure Ratio	12	18
Compressor Efficiency	0.80	0.80
Turbine Inlet Temperature, ^{o}F	2150	2400
Turbine Efficiency	0.85	0.85
Turbine Cooling Air	5%	0
Airflow, lb/sec	3.27	2.40
Engine Weight, lb	175	166
Power, hp	485	460
SFC at Max Power	0.54	0.47

As was pointed out in the previous section, these assured performance improvements are barely able to justify a new engine development program. It should be kept clear that what is being recommended is a component demonstration program to help assess the utility of a later engine program. Also, it is appropriate in this situation to pursue the technology aggressively; consideration of novel technical solutions and new materials should be encouraged.

B. EXPENDABLE ENGINES

1. Current Programs and Future Mission Probability

Of the four classes of engines, the cruise missile engine has the future that is least clear The only thing that comes close to certainty is that there will be some sort of cruise missile in the future. The types of missions that are likely and which are

the likeliest soonest have not been defined by service mission requirements, and some judgment is required here. There are no known current programs to develop new cruise missile engines except the upgrade of the F107 to the F112.

The mission parameters that largely determine required engine performance are range, speed, and altitude. Without too great a simplification, it can be said of each parameter that the values of interest fall into one of two regions.

Ranges for cruise missiles divide very generally between long and short, corresponding to strategic missiles with a range of a couple of thousand miles and tactical missiles with a range of a couple of hundred miles.

The missions can also be divided between low altitude and high altitude. Again, the requirements divide fairly clearly between very low and very high. Because of the survival strategies available to cruise missiles, either they must fly low to be screened from the threat by the terrain or they may attempt to fly over the threat at altitudes of 100,000 feet or so. Intermediate altitudes may be of interest for some reconnaisance missions.

Speed does not divide so neatly as the previous two mission charateristics; there are two motivations to go fast. The first is survivability. The threat to the cruise missile can get off fewer shots within a given lethal range if the cruise missile speed is increased, and in some cases the threat is less likely to get off any shot at all; this can be particularly important during the final penetration of a terminal point defense--for example, during an attack on a ship. The second motivation for increasing speed is target urgency; in certain circumstances, it may be important to attack a target quickly. For example, when defending a ship it may be critical to attack an approaching bomber before it can launch anti-ship cruise missiles, or when penetrating enemy air space, it may be required to suppress the air defense sites rapidly.

For both survivability and target urgency there is continuous increase in payoff with increased speed, and hence the lack of a clean separation between fast and slow. There is, however, a large penalty for supersonic flight. At supersonic speeds, the design of the engine and the airframe is significantly different from subsonic designs, so although the speed payoff may be continuous, there is a clean divide between subsonic, which will typically be mid to high subsonic, and supersonic, which will be greater than Mach 1.5 or so.

All possible combinations make eight possible missions, as shown in Figure 2. This number can be reduced somewhat. Specifically, a long-range, low-altitude, supersonic mission is so difficult, if not impossible, that it is not a foreseeable option; also, it is difficult to picture a high-altitude, short-range mission--whether supersonic or subsonic--that cannot be filled better by a rocket engine.

The long, high, and fast cruise missile (something similar to DARPA's ELITE program, for example) will be very difficult but perhaps not impossible. The challenge to the cruise missile in this case is to keep its weight below that of a small, single-warhead ICBM. Other than lower launch weight, the high and fast cruise missile does not appear to have many advantages over the ballistic alternative. There is great cost associated with supersonic flight; this can be justified either because it enhances survivability or because of the urgency of the target. The survivability of low-flying cruise missiles and ballistic missiles is complementary because a different system is required to attack each one. In contrast, an anti-ballistic missile system and defense against a very-high-altitude, high-speed cruise missile could be very similar. It is difficult to predict whether a high-altitude or a low-altitude cruise missile will be more survivable, but it is hard to picture how a high-altitude cruise missile could be markedly more survivable than a ballistic

CRUISE MISSILE MISSIONS

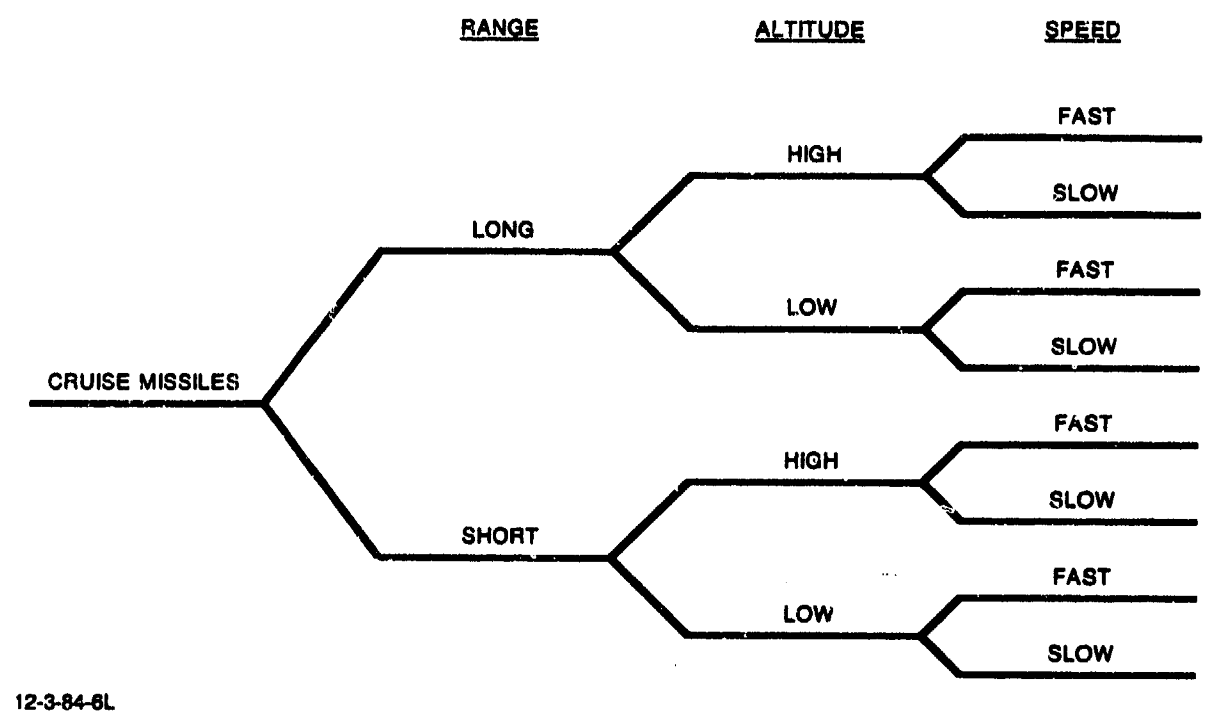

FIGURE 2. Cruise missile missions can be classified by range, altitude, and speed as either long or short, high or low, and fast or slow. This results in a total of eight possible combinations. Some combinations can be eliminated immediately; the long, low, supersonic mission is not possible with foreseeable technology, and short-range, high-altitude missions are better fulfilled by rockets. The five remaining classes of mission are at least potential turbine engine applications.

reentry vehicle. Target urgency could perhaps justify a high and fast cruise missile instead of a low and slow one, but again the competition is really a ballistic missile. There will be very few targets that can wait longer than the tens of minutes of flight time of a ballistic missile and cannot wait the several hours required of a subsonic missile, yet must be struck in the intermediate few hours required of a supersonic missile.

An additional use for a high and fast vehicle is for reconnaisance. There could also be such a mission for a high, slow vehicle. It is difficult to predict the nature of such vehicles, but the total number would likely be very much smaller than the number of cruise missiles.

The remaining strategic or long-range mission is the low, slow cruise missile. This is the current ALCM and Tomahawk and their follow-ons. There seems to be some confidence in the utility of the current ALCM, and presumably the follow-ons will be at least as useful.

The short-range or tactical missions remaining are low altitude, both fast and slow. An example of the low, slow, short-range missile is the current Harpoon. Again, it is probably safe to say that the mission is useful now and will continue to be in the foreseeable future.

The difficulties of supersonic flight impose fewer penalties on the aircraft when the range is short. It is therefore impossible to dismiss as unrealistic the supersonic low-altitude tactical missile as easily as the long-range mission could be dismissed. There are, however, certain constraints that limit the envelope of interesting ranges and speeds. At very short range, the efficiency of the propulsion system becomes so unimportant that a rocket is an attractive, simple alternative to a turbojet. As the range increases, the rocket cannot compete; however, at speeds above Mach 2, the competition is a ramjet. As range

increases further, the slightly better fuel efficiency of the turbojet makes its relative advantage over the ramjet appear to increase; however, in absolute terms the initial weights of both vehicles are growing rapidly as design range increases, making the vehicle a less attractive option. Ultimately, as the range increases, a ballistic rocket that can leave the atmosphere and return begins to compete with the cruise missile.

Taken together, this means that the proposed mission must fall in a box of range and speed that is fairly narrow. The range of a turbojet missile must be greater than about 80 km and less than a few hundred to be preferred to a rocket, and the speed must be less than Mach 2.0 to be preferred to a ramjet. This can be seen in Fig. 3. This shows the initial weight required for cruise missiles designed for various ranges. The plots are for a missile with an L/D of 4.0. The fuel consumption is calculated for a ramjet using military specification inlet recovery and for a turbojet using a pressure ratio of 4.0 and current advanced-technology component efficiencies. Fuel consumption as a function of turbojet compressor pressure ratio was calculated for the conditions given. It was found that a fairly flat minimum occurred between 3 and 5, so the choice of 4 is not critical. The maximum temperature of each engine was limited to 2500^{o}F. With these engine parameters, the ramjet has a thrust specific fuel consumption (tsfc) of 2.18 lb fuel/lb thrust/hour and the turbojet 1.64. The tsfc of a rocket is of interest for comparison. Rocket fuel performance is expressed as the inverse of fuel consumption, that is, thrust-seconds per pound of fuel. A typical value for a rocket motor--that is, fuel plus casing and nozzle--is 200 lb-sec/lb, which is equivalent to a tsfc of 18 lb fuel/lb thrust/hour. The weight-range calculations represented in Fig. 3 are rather simple. They assume cruise conditions throughout, which neglects the operation at lower speeds and when acceleration is required. The engine specific weights of the ramjet and turbojet are assumed

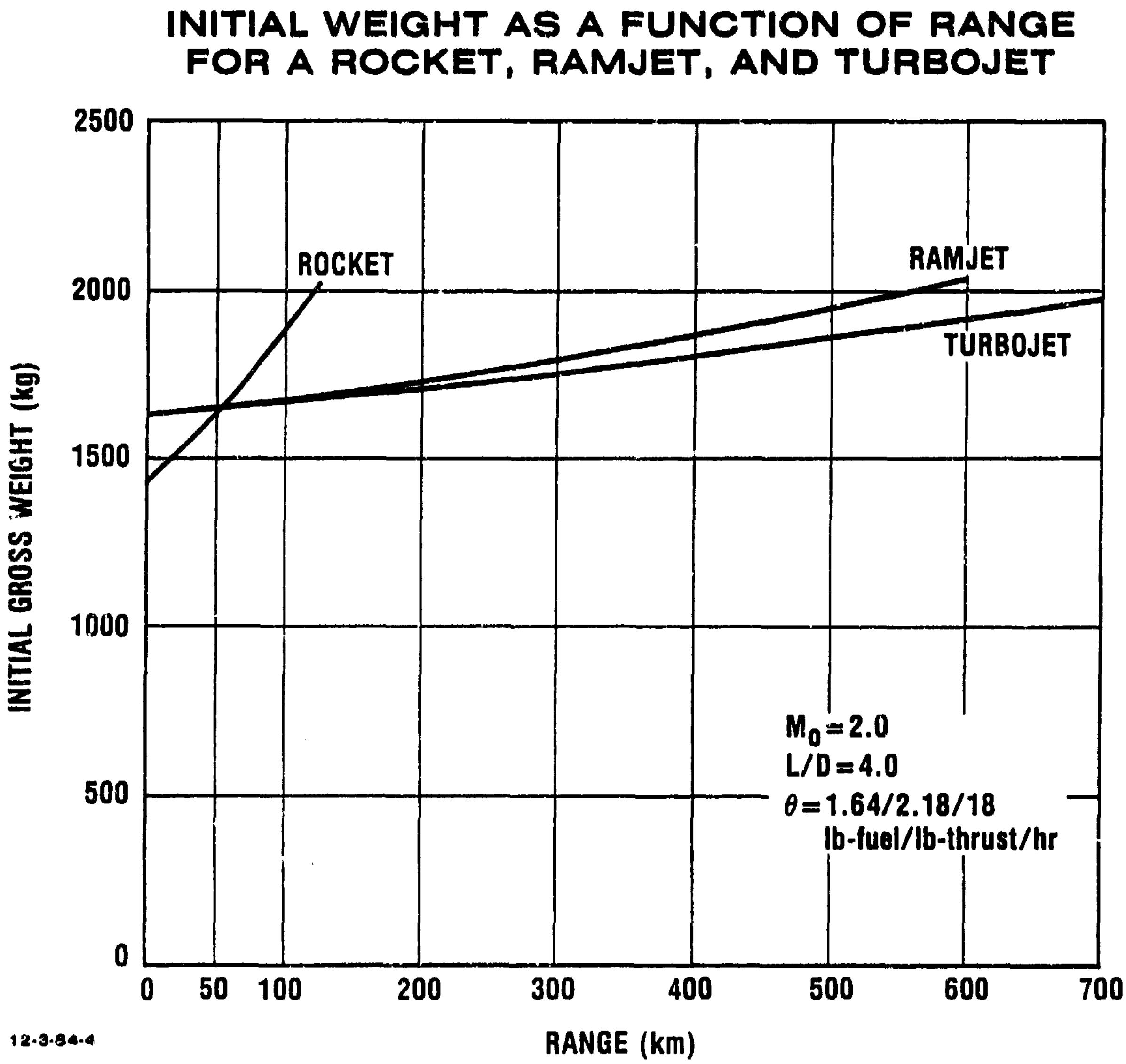

FIGURE 3. These curves show the initial missile design weight as a function of range for a rocket, a ramjet, and a turbojet. Equations used to generate the curves are described in the appendix.

to be the same, although in fact the ramjet would almost certainly be lighter. This is offset by neglecting the weight of the booster rocket required to get the ramjet up to operating speed. This acceleration period for the turbojet is not without penalty; any turbojet optimized for supersonic cruise will not operate at peak efficiency subsonically. The same maximum temperature is used for both types of engines, although achieving this will be easier for the ram than the turbojet. What the figure does not show is the relative cost, complexity, and reliability of ramjets and turbojets; all three favor the ramjet.

All of the above considerations aside, the figure shows that at Mach 2.0 the range required before any appreciable weight difference of, say, 10% appears is approximately 500 km. The life-cycle cost of a missile is dominated in many cases by the costs of the missile carrier. Whenever this is true, missile weight becomes an important parameter. It would appear from the graph, however, that below 500 km the turbojet has no obvious advantage over the ramjet. Moreover, the technical difficulty of achieving a small, supersonic, low-altitude engine is substantial; it is a greater problem than for high-altitude flight. The optimal cycles, pressure ratios, and temperatures may be similar, but absolute pressures, heat transfers, and torque transfers will be much greater because of the higher initial air density.

Under the conditions outlined above, the ramjet will be a stiff competitor for missions less than 500 km. Above 500 km, the turbojet becomes <u>relatively</u> more attractive, but the <u>absolute</u> difficulties increase steadily, bringing the feasibility of any low-altitude supersonic mission into question.

Several factors could shift the relative advantage of the turbojet and ramjet. Turbojets do not compete well at high speeds because the stagnation temperature is so high that little additional work can be added by the compressor to improve the cycle before the compressor discharge temperature is at the

materials' limit. With high compressor discharge temperatures, the fuel-to-air ratio must be kept low, which causes the engine volume specific power to increase and--for actual components--at some pressure ratio the fuel efficiency declines as well. As speed increases, this effect increases. The plots shown in Fig. 3 are for speeds of Mach 2.0. At higher speeds, the advantages of the turbojet rapidly fade until at Mach 3.0 the tsfc of each is approximately the same for 2500°F engines. Increases in material temperature limits allow the turbojet to remain competitive to higher speeds because a higher compressor discharge temperature becomes useful.

Several propulsion penalties make the turbojet relatively more favorable. If radar cross-section requirements call for flush inlets, which substantially reduce the inlet recovery efficiency, the penalty in propulsion performance is less for the turbojet than for the ramjet. To reduce infrared signature, it may be desirable to use less efficient nozzle shapes--for example, slot nozzles. As in the case of inlet efficiency, the engine with the higher specific power is relatively less penalized by these losses (Ref. 1). Note, however, that this does not by itself make the turbojet an attractive option. All propulsion penalties will make both systems larger at a given range and speed; the turbojet will benefit only relatively.

The likely future cruise missile turbine engine missions are judged to be low altitude, subsonic of both short range and long range and high altitude, long range or long endurance at subsonic and supersonic speeds. The high-altitude vehicles may fill cruise missile roles or perhaps surveillance functions. The low-altitude missions, which are follow-ons to the current long-range ALCMs and SLCMs and the short-range Harpoons, are most likely in the near future. The long-range missile clearly places the greatest demands on the propulsion system and offers the greatest potential payoff from propulsion system performance improvements. For any

vehicle, the propulsion system increases in importance as the vehicle range increases. Current long-range cruise missiles have more than half of their initial gross weight taken up by fuel; the weight of the engine is much smaller than the fuel weight. For long-range missiles, the most important engine performance parameter is therefore thrust specific fuel consumption. Engine volume and weight have less leverage for vehicle improvement (Ref. 2).

2. Payoff from Expendable Engine Performance

It is difficult to calculate the mission payoffs of the cruise missile if the mission is not known. However, looking just at carrier costs is illuminating. The B-1 can carry 22 ALCMs. At $200 million per B-1, each cruise missile has a $9 million share in the carrier aircraft. A 20% reduction in cruise missile weight would presumably allow a 20% reduction in assigned carrier aircraft, reducing the per missile cost share by $1.8 million; a 3000 cruise missile fleet savings totals $5.5 billion. Costs could also be based on total life-cycle costs of the carrier; these are hard to predict for the B-1, but for a wide variety of vehicles the life-cycle costs are between two and three times procurement costs; in this case fleet savings could exceed $25 billion. This neglects savings in cruise missile structure. Clearly, the potential savings are enormous.

Much more modest savings are calculated if one assumes that the B-52 will serve as a cruise missile carrier and that procurement costs are "sunk." In this case only the operating and maintenance (O&M) costs of the B-52 are allowable. The annual B-52 O&M costs are about $40 million. If each carries 24 cruise missiles, this is a cost of $1.8 million per missile. A 20% decrease in cruise missile weight yields a $0.35 million saving, which yields a 3000 cruise missile fleet saving of just over one billion dollars.

There might be substantial benefit in re-engining the current ALCMs. This would probably not be used to reduce weight because the only way to do that would be to offload fuel; instead, a new engine could be used to increase range at constant weight. If the increase in range and the greater standoff it permits makes the difference between the carrier's surviving and being destroyed, the payoff is huge. The calculation of carrier survivability is complex and sensitive to assumptions and will not be attempted here; what can be said safely, however, is that present cruise missile range is not already excessive.

3. Technology Required for Expendable Engine Improvements

As shown in Appendix A, the constant-altitude range of an aircraft is

$$R = (A/\Theta)\ (W_i^{1/2} - W_f^{1/2})$$

where A is a parameter related to the aerodynamic efficiency of the vehicle, Θ is the thrust specific fuel consumption, W_i is the initial weight, and W_f is the final weight. A plot of W_i as a function of Θ is shown in Fig. 4 for a missile with the range of the current ALCM.

The current ALCM is about half fuel by weight at launch and is, therefore, near the knee in the exponented weight-range relationship. Even so, difficult improvements in tsfc are required to effect substantial reductions in weight. At the current ALCM range the weight leverage from tsfc is one to one; that is, a one percent reduction in weight requires a one percent reduction in tsfc. At shorter ranges the sensitivity of weight to tsfc is less; at longer ranges it rapidly becomes greater. A 20 percent reduction in tsfc should be attainable, and the resulting 20 percent reduction in weight would be significant.

INITIAL AIRCRAFT WEIGHT AS A FUNCTION OF SPECIFIC FUEL CONSUMPTION

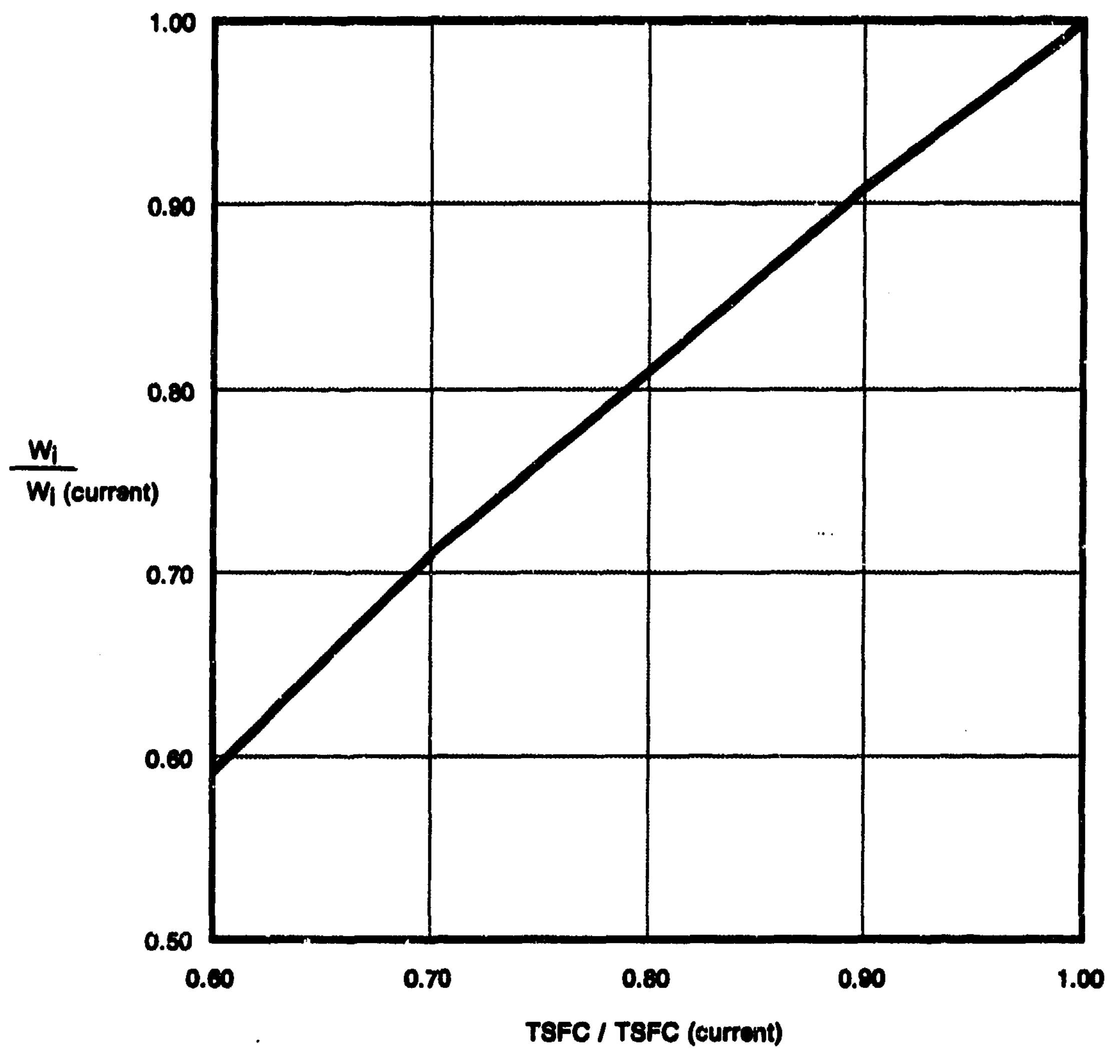

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FIGURE 4. At the range of the current ALCM, incremental improvements in TSFC have approximately a one-to-one payoff in incremental weight reduction. As range increases this sensitivity increases. (The curve in this figure was calculated assuming constant engine specific weight equal to the current F107; because engine weight is a small part of total weight, any error introduced is small.)

A 20 percent tsfc reduction would be a difficult task, but not as difficult as it may first appear because the improvement is here measured relative to the current cruise missile engine, the Williams F107, which is a rather old design and does not exploit the most recent technology, nor was the engine originally intended for or optimized for a cruise missile.

Even with the present engine core, the tsfc could be substantially improved by increasing the airflow and bypass ratio, which improves the propulsive efficiency. This, however, requires a larger engine, which in turn causes packaging problems for the cruise missile. There is benefit from small cruise missile size with bomber- and ship-launched missiles. All other things being equal, the smaller, the better, but it is especially true with submarine-launched missiles where the Navy maintains a requirement that cruise missiles be launchable through standard 22-inch torpedo tubes. Some submarines have been fitted with vertical cruise missile launch tubes that allow the torpedo tubes to be reserved for torpedoes and allow more rapid firing of the cruise missiles. If the trend toward vertical launch tubes continues, then perhaps the 22-inch diameter requirement can be removed. In the meantime, this places constraints on total air flow (which largely determines engine cross-sectional area).

Figures 5, 6, and 7 show the tsfc while varying, one at a time, the efficiency (η), overall pressure ratio, and turbine inlet temperature (TIT). The calculation used to generate the data shown assumed a constant total air flow equal to that of the current F107. The graphs are really useful only to show sensitivities since no single engine parameter will be improved to improve overall performance; any new technology program will attack several simultaneously. The single efficiency used in Fig. 5 is the polytropic efficiency of both the compressor and turbine. The efficiencies will not be exactly the same for the two components but close, and it is a convenient way to represent

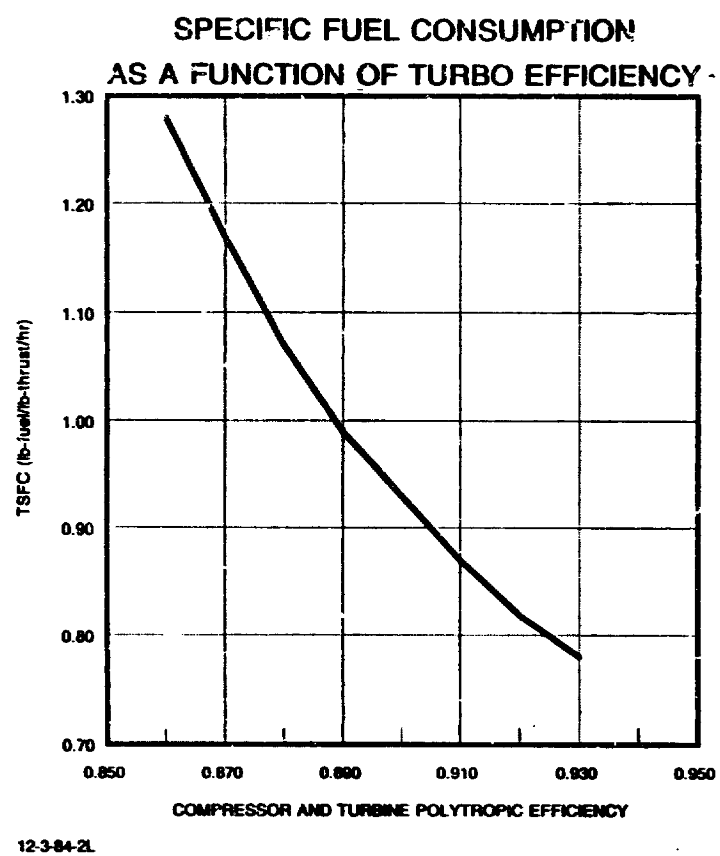

FIGURE 5. This curve shows TSFC as a function of turboefficiency. If the compressor and turbine have equal polytropic efficiency, then it can be used as a single measure for both. This assumption is only approximate, but the polytropic efficiency is a good measure of clearance control, overall aerodynamic design, and tolerances.

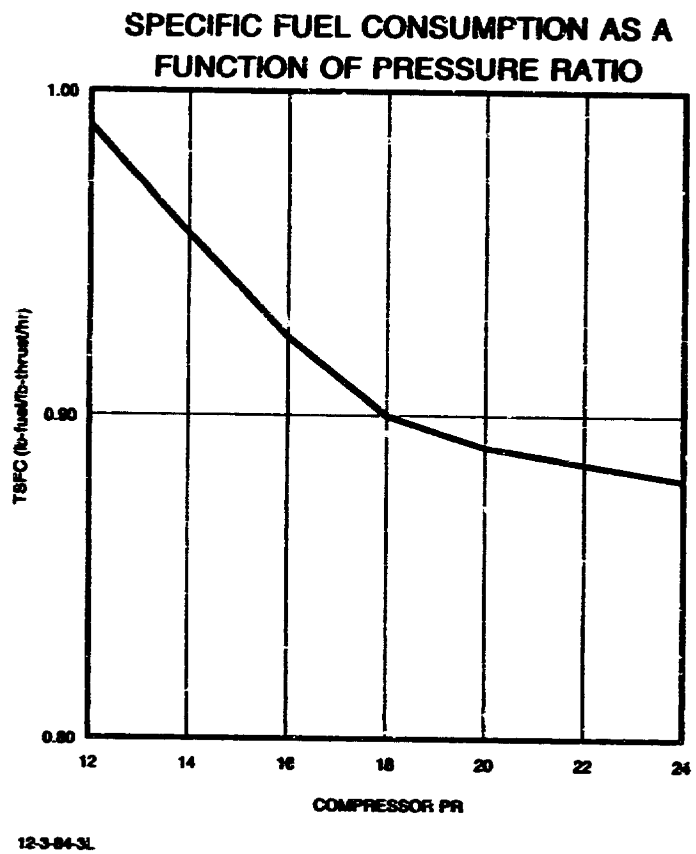

FIGURE 6. This curve shows TSFC as a function of pressure ratio, assuming the efficiencies and TIT of the current F107.

the general level of technical capability in aerodynamic design and clearance control. The increase in efficiency will increase the fraction of energy extracted from what is theoretically available from any given thermodynamic cycle. The overall performance improvement as a function of efficiency appears dramatic; that is, the performance is a very sensitive function of efficiency. Yet this is somewhat misleading because each percentage increase in efficiency is a very difficult technical challenge; an increase of just a few percent may be as difficult as, say, a factor-of-two increase in pressure ratio over the current engine.

Figure 6 shows tsfc as a function of pressure ratio (PR). For an ideal Brayton cycle the ideal thermodynamic efficiency depends only on PR; in fact, the thermodynamic efficiency is the same as a Carnot cycle with the same PR. Whereas an increase in η increases the fraction of thermodynamically available energy extracted, the increase in PR increases the thermodynamically available energy.

Finally, Fig. 7 shows the tsfc as a function of turbine inlet temperature. TIT does not increase the thermodynamic efficiency of an ideal Brayton cycle, but in a real turbofan application it can reduce tsfc by increasing the specific power of the core, which allows a reduction in the work penalty extracted by inefficiencies in the compressor and turbine. The smaller core flow results in a larger bypass ratio to keep thrust constant and, if the fan efficiency is greater than the product of compressor and turbine efficiencies (which is always so), the total work loss is reduced. In this somewhat indirect way, decreases in tsfc can result from increases in TIT.

For similar reasons, increases in TIT become attractive in vehicles with large installation losses. Large losses can result from nonpropulsion considerations; for example, flush inlets to

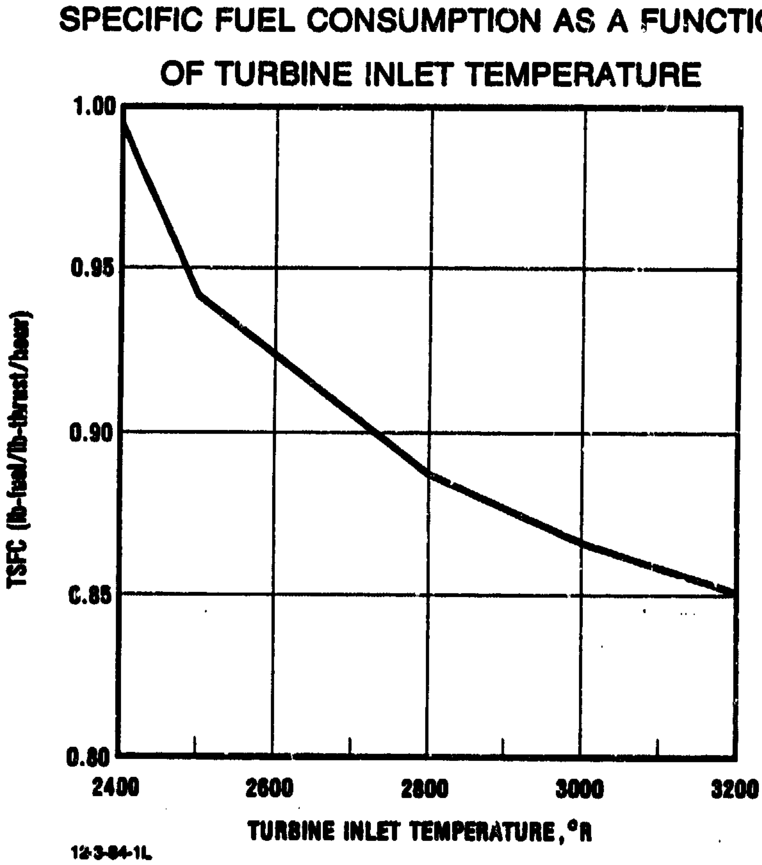

FIGURE 7. An increase in turbine inlet temperature (TIT) of the core of a turbofan improves TSFC. This curve assumes the current F107 pressure ratio, turboefficiencies, and airflow. Although the curve suggests that substantial TSFC improvements are possible, the increases in TIT are challenging and for large increases require new types of materials. Temperatures are in degrees Rankine.

reduce radar cross section or slot nozzles to reduce infrared signature. In general, engines with higher specific power will be penalized less by such losses than engines with lower specific power. If future missile designs require high installation losses, the motivation for higher TIT will increase.

An important interaction must be pointed out. Small turbine engines have unique problems due to their smallness. For example, the efficiency of the turbomachinery is less than for large engines because the components are smaller without a proportional decrease in tolerances and clearances. If increases in PR and TIT are postulated, this implies higher specific power and smaller core engines, which may make just maintaining component efficiency difficult. Clearly, an engine program will try to advance capabilities on several fronts but, with the difficulties of just maintaining efficiency, Fig. 8 is of interest; it shows the combined effects of increasing PR and TIT while holding η constant.

If improvement could be made on all fronts, substantial tsfc advances are possible, for example, if it were possible to develop a new engine with two points better component efficiencies, TIT of 2800°R, and a PR of 18, would then result in a reduction of 30% in tsfc even with current airflow limits. This should be able to justify a new engine program (Ref. 2).

Expendable engine research programs have the potential for a broad application to other engine types. Because of the limited life requirements, the program can stretch technology further, particularly in materials. This allows the characterization of new materials and their use in an engine environment so that acceptance of the materials in other engines, particularly man-rated aircraft engines, will be easier and the risks lower.

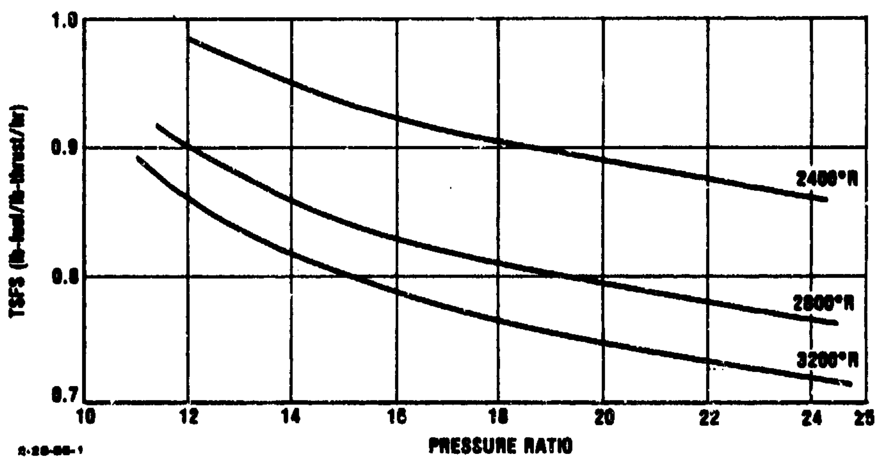

FIGURE 8. These curves show the effect of increases in both pressure ratio and turbine inlet temperature. Because the components get smaller as PR and TIT increase in an engine of given thrust, it becomes harder to achieve high component efficiency. For this reason the "advance" in component efficiency in these curves is just <u>maintaining</u> current efficiency.

C. AUXILIARY POWER UNITS

1. APU Missions

Included in the category of APUs are ground power units, mobile electric power, and shipboard housekeeping power supplies.

Aircraft APUs typically provide housekeeping and environmental power while the aircraft is on the ground. They also are used for main engine starting. APUs have approximately as much run time as main engines, but the power levels are much smaller, from 1% to 3% of main engine power, so total vehicle performance is insensitive to improvements in APU performance. For transport aircraft a better comparison is betwen APU plus fuel weight and cargo plus fuel weight. Again, the APU is only a few percent of the aircraft's total discretionary weight.

There is a continuing requirement for mobile electric power units over a wide power range (~10-100 hp), but the importance of acquisition cost generally overrides any requirement for very low weight and volume, and diesel engine sets are usually procured. Also, the quantities procured are not very high, particularly over about 60 kW where turbines might be most suitable.

The future situation with APUs is unclear. There is a potential future need for APUs capable of rapid high-altitude restart of fighter aircraft and for continuous operation of aircraft APUs. These requirements would be for units of 400-500 hp (Ref. 3). There is also a possible requirement for APUs for environmental protection of combat vehicles and APUs for medium helicopters; these requirements would be for units of 100 hp or less. None of these requirements is firm. The density of modern fighters is high and is tending to increase; at the same time the power requirement of the APU may increase substantially. These two effects together emphasize increased engine power density (hp/cu ft). (Reference 3 suggests a need for roughly doubling

the current power density over state-of-the-art APUs.) The potential land vehicle APU requirement also emphasizes increased power density if the APU is to be inside the armor envelope.

The aerothermodynamic performance of the APU is not the only possible area of improvement. Reliability and ease of maintenance are particularly important considerations for aircraft APUs.

2. Technology Required

The increased power density that would benefit both the potential future fighter and combat vehicle missions implies increased temperatures. Improved specific fuel consumption would become increasingly important if continuous APU operation were required; this demands increases in pressure ratio and component efficiencies.

These technical goals of increased temperatures, pressure ratios, and efficiencies are exactly those that would be set for man-rated and expendable engine technology programs and both the man-rated and expendable engines are likely to have higher performance payoffs than the APUs. It is therefore difficult to justify a technology demonstration for APU development specifically; a reasonable course is to use for APUs the technology developed in programs designed with man-rated and expandable engines in mind. There is no unique APU technology that warrants a technology demonstrator.

This is not to say that current APUs cannot be improved. Many units now in service are of old design and are old in technology. Much techical progress has been made and is available, yet has not appeared in existing APUs. Improvement in performance could be achieved in future APUs just by using the new technology in hand. When the mission became clear and specific requirements of the APU were known, then FSED could be entered directly without separate preceding APU technology demonstrations.

The high reliability required of APUs could be addressed to some degree by technology demonstration programs. This is, however, better treated by careful system design, in a system demonstrator phase, for example, by testing during FSED, and through product improvement programs after the engine has been fielded.

D. LAND VEHICLE ENGINES

1. Current Programs and Future Mission Probability

Land vehicle propulsion is a fairly new mission for turbine engines, and there is in fact only one example in production or use, the M1 main battle tank powered by the 1500 hp AGT1500. Land vehicles are, in general, less sensitive to propulsion system weight than aircraft. Also, turbines have problems of low efficiency in small sizes, so they compete less well with diesels as the horsepower requirement is reduced; coupled with the relatively lower horsepower of land vehicles compared to aircraft and the lower power duty cycle, turbines have not been able to find the broad range of application in ground vehicles that they have with aircraft.

Only in the case of the heavy, highly powered, and heavily armored main battle tank (MBT) is the combination of power requirement and vehicle sensitivity to propulsion system performance such that the turbine is a candidate. Even for the MBT the turbine is not a clear choice; only the M1, from among the few similar western MBTs, is turbine powered. The Army now has a program to develop a follow-on to the AGT1500 to power the follow-on to the M1; this program, called the Advanced Integrated Propulsion System (AIPS), is a pair of competitive technology demonstration programs, one for a turbine and one for a diesel. Clearly, the tank propulsion community does not consider the

choice between turbine and diesel to be clear-cut. The diesel does not suffer equally with the turbine from the performance penalties associated with small size; because of this there will be, for any given application, a size above which the turbine is the preferred power source and below which the diesel is, and a middle ground where they compete. Where the crossover occurs is a function of technology and mission. Technical advances that asymmetrically favor the diesel or turbine can shift the cross-over point up or down, respectively. If one assumes that the choice of propulsion system is a result of careful, rational analysis, one can deduce empirically that the current state of technology must be such that the crossover point for MBTs is at about 1500 hp.

The AIPS program will generate a pair of technology demonstration engines early in the next decade. The AIPS program will generate an integrated propulsion package including engine, heat exchangers, air cleaners, and, very important, transmission. This means that, when the technology demonstration program is finished, the engine will be much further along toward the initiation of FSED than an aircraft engine would be at that end of its comparable demonstration phase. This is partly a matter of the definition of the end of demonstration, but it should also be a reminder of the highly interactive nature of the land vehicle propulsion system. If all goes according to plan, the AIPS-derived engine should be ready for the next tank if new models continue to appear every 20 years or so.

The possible new application that turbine power could find in combat vehicles is toward less power in lighter vehicles such as armored personnel carriers and infantry fighting vehicles (which together we call "light combat vehicles" -- LCVs). These types of vehicles require engines of less than 900 hp, perhaps as low as 600 hp (Ref. 4). Turbine engines will encounter two hurdles in moving into this power range. First, the turbine will

suffer from smaller-sized components and will not be able to compete with the diesel. Second, the lighter vehicle will, in general, be less sensitive to propulsion system improvements so the payoff from a hypothetical improved turbine propulsion system would be less, making economic justification of an expensive engine development program more difficult. This second point is augmented slightly because the sensitivity per vehicle must be multiplied by total fleet costs. The LCV fleet outnumbers the tank fleet typically by slightly less than two to one, but the tanks individually cost more than twice as much as the LCV; therefore, the total fleet costs for the tanks are usually larger than those for the LCVs.

2. Performance Payoff

Table 4 shows the cost sensitivities to propulsion performance of MBTs and LCVs based on the M1 and the M2/3 (Ref. 4). These numbers are the proportional reduction in vehicle weight for an incremental reduction in the specified engine performance parameter. The first LCV column shows the sensititivity of the current vehicle, but the propulsion sensitivity is somewhat misleading when applied to turbine improvements. For example, the high sensitivity to specific weight is due, in part, to the rather heavy current power pack in the M2/3. The column marked LCV (turbine) is for a hypothetical M2/3 type vehicle powered by a turbine engine with the same specific performance as the AGT 1500 (which, considering the smaller turbine size, would be technically more challenging). The first LCV column gives some measure of the payoff in going from a diesel to a turbine. The LCV (turbine) column gives a better representation of the sensitivity to improvements in turbine performance. There is less turbine performance leverage in the LCV than in the tank.

Table 4

Engine Parameter	MBT(M1)	LCV(M2/3)	LCV(Turbine)
sp. fuel consumption	0.26	0.15	0.22
sp. weight	0.27	0.43	0.22
sp. volume	0.29	0.10	0.06
sp. cost	0.12	0.11	0.13

In summary, the turbine engine is an unlikely but not impossible power source for LCVs in the near future for these reasons: (1) the current crossover point between turbine and diesel preference is near 1500 hp, (2) at smaller sizes turbine performance becomes relatively worse compared to the diesel, and (3) even postulated superior small turbine performance may not be adequate because the per-vehicle and fleet cost leverage is even less than for MBTs, making economic justification of a development program more difficult. At least there is no question concerning the likelihood of the LCV mission; there are now tens of thousands of APCs, IFVs, and self-propelled artillery pieces, and no known analysis or prediction suggests that this sizable fleet will become much smaller in the foreseeable future. It is of course possible that some major technical advance will make the turbine competitive at lower powers, but it must also be remembered that major advances in diesel technology are simultaneously being pursued.

3. Technology Required

Research in land vehicle engines is not as broadly applicable as work on aircraft engines. The AIPS program is but one manifestation of the highly integrated nature of the propulsion system design. For example, for almost all overall performance measures the vehicle is as sensitive to transmission performance as it is to engine performance, and the air cleaner and heat exchangers take up

as much volume as the engine. Furthermore, these several components critical to land vehicle turbines are of little or no use for other turbine applications; therefore other engines will not benefit greatly or directly from land vehicle propulsion component research. The land vehicle engine can benefit from developments in other engine areas, especially rotating component developments for aircraft engines, although even here the land vehicle engine has some unique requirements such as variable geometry turbines. It seems likely that land vehicle engine development programs will continue to borrow, to the extent possible, the rotating component technology from aircraft engines and concentrate their resources on those components unique to land vehicle applications. This implies that the aerothermodynamic gains will be made largely in other programs and the land vehicle propulsion program will yield gains in transmissions, heat exchangers, and so on. It is difficult to assess the relative likelihoods of increasing TIT in a helicopter engine and increasing the power density of a transmission; it is therefore difficult to assess the relative likelihood that a program will yield advances that would justify the costs of the program.

The AIPS program adequately anticipates requirements of the next-generation MBT. The program also will dominate the funding for land vehicle propulsion until its completion. A similar program for smaller engines is possible; the reasons why it may be technically premature are pointed out above. In any case, the resources may not be available. Presumably, at about the same time that the next generation of MBT is required, a follow-on to the M2/3 LCVs will be needed. It may be that turbines will miss that opportunity unless the LCV generation can be stretched by half (or turbines may have to wait until the generation after next). This would require initiation of a development program in the mid-1990s as the AIPS program is being completed.

Right now it would be worthwhile to review design studies to determine what the payoffs would be to LCVs from turbine power plants and to identify components critical and unique to land vehicle applications. These studies could then be followed by component technology demonstrations of unique components--for example, regenerator seals--in anticipation of the possibility of a small turbine program following.

IV. CURRENT R&D PROGRAM OPTIONS; CONCLUSIONS AND RECOMMENDATIONS

A. COMPARISON OF SIZE REQUIREMENTS FOR DEMONSTRATORS

If the preceding judgments regarding mission probability are correct, there is a fortuitous agreement in the size of useful demonstrators. To reiterate: (1) for the man-rated aircraft class a 500 hp helicopter engine is needed to replace the sizable fleet of small observation helicopers; (2) for the cruise missile a turbofan engine is needed to replace the follow-on to the ALCM and Tomahawks in the range of 600 to 1000 pounds thrust; (3) for land vehicles a potential future configuration, for which a turbine engine is not being developed now, is the lightly armored combat vehicle of 30 tons or less that will require engines of between 500 and 900 hp; and (4) for APUs the mission that is most likely to warrant any sort of demonstrator is a capability of high-altitude restart of high-density fighters, which may require power levels up to 400 hp.

A general picture of the development history of domestic engines of various sizes is illustrated by Fig. 9. The abscissa is the number of years from qualification test, and the ordinate is the size of the engine (note that thrust and shaft engines have been forced rather roughly onto the same axis). Each engine is represented by a pair of boxes; the rightmost box is the power as the engine first appeared, and the leftmost box is the power to which the engine was later product-improved. Two trends are clear from the chart: first, there has not been a domestic small engine development program initiated in a long time; and second, the engines that were once on the low end of the power scale tend

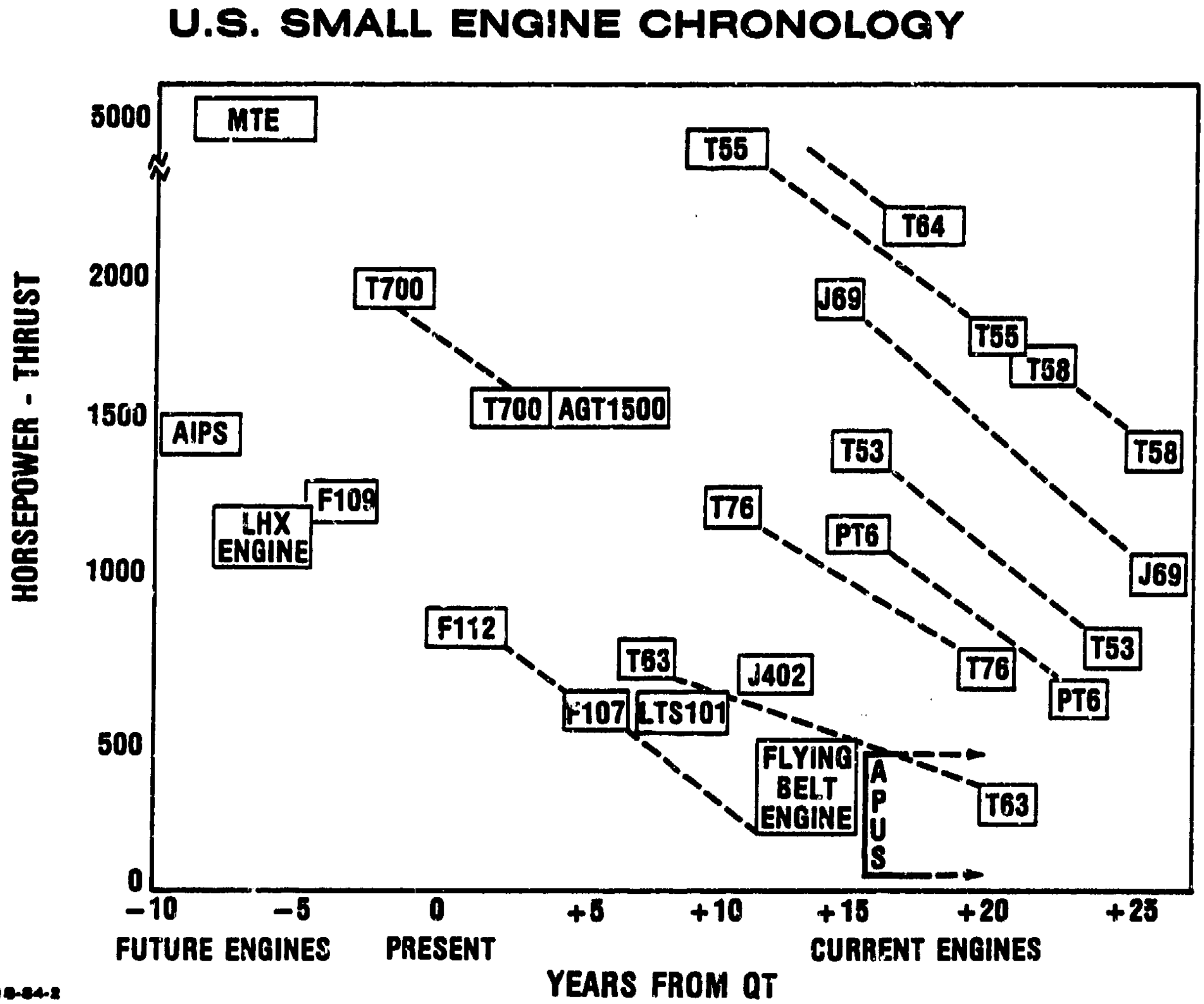

FIGURE 9. This graph shows U.S. small engines arranged by power or thrust and year from qualification test (QT). Each engine is represented by a pair of boxes; the right-hand box is the power when the engine was first introduced, and the left-hand box is the power to which the engine eventually evolved. Note that no new 500 hp class engine has begun recently.

to evolve out of that power rating into more powerful engines. A technology program of some sort in the 500 hp class would be appropriate for each of the four engine classes and would fit nicely into the void that appears in the lower left-hand side of the chart.

Coincidentally, this is also the power range where many foreign companies are entering the world market. Foreign competition as such is not a concern of DoD; however, if the missions outlined previously are important and are judged to warrant DoD support, it follows that the missions are of great enough military significance that foreign competition in the mission area is of military significance as well.

B. COMPARISON OF TIMING REQUIREMENTS OF DEMONSTRATORS

The resources are not available to do everything at once, nor would it be efficient even if it were possible. The recommendations regarding the relative timing requirements are based on four criteria:

1. the payoff to the mission
2. the urgency of the mission
3. the direction of technology flow, and
4. the presence or absence of competing programs within the class.

Some examples of how the critera can be applied to timing are as follows.

For the first, APUs do not seem to have as great a payoff as cruise missile engines, so the cruise missile engine development should precede that of the APU.

The second criteron could decide between, for example, 1500 hp helicopters and tank engines if they were judged to have equal

payoffs from new propulsion technology, but if a replacement tank is needed in 10 years and a replacement helicopter is needed in 20, the tank engine development should precede that of the helicopter engine.

The criterion of direction of technology flow implies that technology does not flow equally in both directions between categories of engines and if, by the above criteria, the helicopter and tank engine were judged equal, then one must consider how each may help the other. The helicopter engine will develop rotating turbomachinery of high efficiency and materials with high-temperature capability that will aid the tank engine. The tank program must devote substantial resources to other components such as transmissions, heat exchangers, and so on. These tank developments, if they were to come first, would not aid the helicopter engine program. Moreover, the sensitivity of the tank to propulsion system performance is not as great as that of the helicopter, so the tank program may make do with a level of turbomachinery performance that is unacceptable to the helicopter. The converse is not true; the tank user will be happy to have the highest-performance turbomachinery possible if the helicopter program pays for its development. By this criterion, the helicopter engine program ought to precede the tank engine program.

The fourth criteron takes into account programmatic and fiscal realities. For example, if, by all of the above criteria, the LCV, 500 hp helicopter, and cruise missile engines were judged of equally high merit, consideration must be made of the AIPS and LHX programs that will dominate funding for land vehicle engines and man-rated aircraft engines. There is no competing Air Force or Navy expendable engine program, so by this criterion the cruise missile program would come first, not because it is most important but because only it is able to find a niche in the budget.

Applying these four criteria to the four engine categories reveals a varied picture. The man-rated aircraft engines appear to justify component demonstration in the 500 hp size, but it is not a clear-cut case. The financial arguments are sound, and it is fairly certain that the mission will appear; however, that is not official. The performance payoffs for man-rated engines are the highest; this justifies the best technology, so the flow of technology down to other applications occurs rather naturally. All this might suggest that a 500 hp helicopter engine technology demonstrator ought to be started now.

For expendable engines the payoff is available just in carrier aircraft costs if a long-range mission is assumed. Again, the mission urgency is difficult to judge because the Air Force seems uncertain about the cruise missile mission; however, there will almost certainly be a follow-on to the ALCM, and the current F107-F112 technology could be advanced substantially. The technology flow direction is a key supporter of an expendable-engine program. Expendable-engine technology demonstrators could be a test bed for new materials. Because of the short-life requirement, new materials can be tried in expendables long before the materials could be considered for man-rated aircraft. Examples include ceramics and coated carbon-carbon composites. Just because the materials are intended for expendable engines does not mean that they are restricted to short-life applications; valuable experience with the materials will be gained in design, and the materials will be characterized in an engine environment. This is a necessary step before the materials will be useful in a man-rated engine.

The calculation of whether to start a development program involves technical risk, mission payoff, and program cost. As was pointed out in the discussion on helicopter mission payoff, as a technology matures the incremental improvements are smaller and the payoff less, but the development programs remain at roughly

constant cost. There may be ways to reduce program costs with computer-aided design, perhaps, but the attractiveness of a development program is greater if a bigger performance gain is possible. New materials developed for and characterized in expendable engines could provide an opportunity for a large gain in man-rated engine performance; this would make a man-rated engine development program more attractive.

There is no other known program by the Air Force or Navy with which an expendable engine demonstrator would compete directly. Very little argues against starting an expendable-engine technology demonstrator soon. If the next cruise missile mission were defined very soon, a system demonstrator of a turbofan engine would be appropriate. Failing that precision in mission definition, which seems likely, a turbofan core technology demonstrator could usefully advance the technology while awaiting mission details.

The land vehicle engine mission has payoff with the MBT application. That is already covered by the AIPS program. The payoff in LCVs is less, and it is not at all clear that the turbine is an attractive option at the lower power. Other applications would benefit little from the component developments necesssary for a 500 hp LCV engine, but an LCV engine could benefit from turbomachinery developed for man-rated and expendable engines.

APUs have no new mission defined, and when one appears there is every chance that FSED could be entered directly without a demonstration program. Two of the most important APU characteristics, reliability and low cost, can frequently be developed through product improvement.

C. OVERALL PROGRAM RECOMMENDATIONS

Tying all this together into a coherent program requires some overall judgments about the relative priorities of the criteria above. There is, in this case, a fortuitous coincidence in the overlap in power requirements at about 500 hp. Starting an expendable-engine gas generator core technology demonstrator now allows the commencement of a technology demonstrator as soon as the mission is well enough defined for decisions on required specific thrusts, bypass ratios, and so on. The expendable-engine gas generator program should include use of new materials.

The required man-rated engine is approximately the same size, but a gas generator for it is premature. A 6.2 component program could develop new components that would perhaps use materials developed in the cruise missile program. It is even possible that helicopter components could be tested in the expendable-engine gas generators. This program would advance the component technology that would be used in a gas generator or engineering technology demonstrator to be started up after the LHX engine program is finished or firmly committed.

Some of these components, even if developed with a man-rated application in mind, would be of benefit to all small turbine engines. For example, a high-temperature radial turbine using either cooling or high-temperature materials would find many applications; small engines have a problem in finding space for diagnostic and development instrumentation, and progress in the development of miniaturized instrumentation could have application in all following development programs.

AIPS is already supporting the most likely land vehicle mission. The next most likely mission is for a 500 hp engine for

an LCV. Whether this is a plausible mission or not requires detailed analysis. A reasonable approach is to review existing studies and carry out further paper studies of the payoff of a turbine engine propulsion system in an LCV and the leverage from improvements in propulsion performance. If these studies indicate that a turbine engine for an LCV is plausible, 6.2 component development could be started for those components unique to land vehicles such as heat exchangers and air cleaners.

In the cases which are foreseeable, the development of new APUs can be accomplished by entering FSED directly when the mission requirement develops. Whenever that is in the future, it will benefit from the designs, instrumentation, and materials developed by other programs.

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*No classified information from any of these references appears in this paper.

APPENDIX

RANGE-WEIGHT RELATIONS FOR AIRCRAFT

RANGE-WEIGHT RELATIONS FOR AIRCRAFT

The weight, W, of an aircraft decreases as fuel is consumed. The incremental weight change, dW, is

$$dW = -\Theta \cdot Th \cdot dt \qquad \text{A-1}$$

where Θ is the thrust specific fuel consumption (weight of fuel per unit time per unit thrust), Th is the thrust, and dt is the incremental time.

Rewritten for dt,

$$dt = - \frac{dW}{\Theta \cdot Th} \qquad \text{A-2}$$

The distance covered, s, is the time times the speed, V, or

$$ds = \frac{-V \cdot dW}{\Theta \cdot Th} \qquad \text{A-3}$$

Total range R is the integrated distance between initial weight, W_i, and final weight, W_f, or

$$R = \int ds = - \int_{W_i}^{W_f} \frac{V \cdot dW}{\Theta \cdot Th} \qquad \text{A-4}$$

The weight is equal to the lift. The equation for dynamic lift is:

$$W = \text{Lift} = \frac{1}{2} \rho S C_L V^2 \qquad \text{A-5}$$

where ρ is the air density, S the lifting area, and C_L is the lift coefficient.

Rewritten for speed,

$$V = \sqrt{2W/\rho S C_L} \qquad \text{A-6}$$

then R becomes

$$R = \int_{W_i}^{W_f} \sqrt{\frac{2}{\rho S}} \frac{\sqrt{C_L}/C_D}{\Theta} \frac{dW}{\sqrt{W}} \qquad \text{A-7}$$

Note the speed, V, does not appear explicitly in the range equation. Assume that $\rho, \sqrt{C_L}/C_D$, and Θ are constant. Constant ρ implies constant altitude which, for a low altitude cruise missile, is a good approximation. Constant $\sqrt{C_L}/C_D$ implies choosing the speed such that this is true which is or is not a good approximation depending on whether one chooses to do it but it is at least possible (and, as will be shown below, maximizes R). Constant Θ implies that fuel efficiency is insensitive to thrust; this is approximate but Θ does not vary by more than 10-15% from an average value during a typical mission so no great error is introduced (this approximation gets worse as range increases).

With these assumptions the range is

$$R = \frac{2}{\rho S} \frac{\sqrt{C_L}/C_D}{\Theta} \int_{W_i}^{W_f} - \frac{dW}{\sqrt{W}} \qquad \text{A-8}$$

Note that if speed is adjusted such that $\sqrt{C_L}/C_D$ is kept at a maximum, then the range is maximized (assuming Θ is constant while speed and weight, which implies thrust, vary).

If the terms $\sqrt{\frac{2}{\rho S}}$ $\sqrt{C_L}/C_D$ are lumped together as an aerodynamic parameter A, then the range becomes

$$R = \frac{A}{\Theta} (\sqrt{W_i} - \sqrt{W_f}) \qquad \text{A-9}$$

The relation among R, Θ, and W_i requires elimination of W_f. Express W_i as the sum of a payload, structure, fuel, and engine weights, namely,

$$W_i = W + W_S + W_F + W_E \qquad \text{A-10}$$

$\sqrt{2/\rho S}$ $\sqrt{C_L}/C_D$

Wp is given. Assume that the structure is a fraction, k, of the initial gross weight, then

$$W_S = kW_i \qquad \text{A-11}$$

Assume that the engine weight is proportional to the maximum required thrust, that is, thrust at maximum weight or W_i so

$$W_E = E \cdot Th_{max} \qquad \text{A-12}$$

where E is the engine specific weight (weight per unit thrust) and Th is the thrust.

The thrust is related to the weight by

$$Th_{max} = \frac{g \cdot W_i}{C_L/C_D} \qquad \text{A-13}$$

where g is the acceleration due to gravity (to convert from weight to force). W_E is then

$$W_E = \frac{gW_iE}{C_L/C_D} \qquad \text{A-14}$$

Returning to W_i in equation A-10

$$W_i = W_p + kW_i + W_F + \frac{gW_iE}{C_L/C_D} \qquad \text{A-15}$$

The final weight, W_f, is just the initial weight minus the fuel or

$$W_f = W_p + W_i \left(k + \frac{gE}{C_L/C_D}\right) \qquad \text{A-16}$$

Equation A-9 then becomes

$$R = \frac{A}{\Theta} \left\{ \sqrt{W_i} - \sqrt{W_p + W_i \left(k + \frac{gE}{C_L/C_D}\right)} \right\} \qquad \text{A-12}$$

All of the above variables are basic engine or aircraft performance parameters that are known or can be estimated; this allows calculation of weight and range design relations for an aircraft. This equation is used to calculate the cruise missile weight and thrust specific fuel consumption relations in Section III.B.3.